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## TESTS OF THE FATIGUE STRENGTH OF CAST IRON

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION  
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE ALLIS-CHALMERS MANUFACTURING COMPANY

BY

HERBERT F. MOORE  
STUART W. LYON  
NORMAN P. INGLIS



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UNIVERSITY OF ILLINOIS  
ENGINEERING EXPERIMENT STATION

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ENGINEERING EXPERIMENT STATION

PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA



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# TESTS OF THE FATIGUE STRENGTH OF CAST IRON

## I. INTRODUCTION

1. *Introductory.*—Very few test data are available on the capacity of gray cast iron to resist repeated stress. In general, gray cast iron is not widely used for machine and structural parts subjected to repeated stress, but cylinders of steam engines, internal combustion engines, and pumps, pistons, valves, cast-iron water and gas pipes, parts of machine tools, machine frames, and levers in the weighing mechanism of scales and testing machines are common examples of cast-iron parts subjected to repeated stress, although fatigue strength is not usually the major factor.

The Allis-Chalmers Manufacturing Company of Milwaukee, Wisconsin, recently made arrangements for a series of fatigue tests of gray cast iron to be made in the laboratories of the Investigation of the Fatigue of Metals at the University of Illinois, which have been in operation since 1919.\* The information secured in the carrying out of these tests by no means covers the entire subject of fatigue strength of cast iron, but it is believed that the publication of these test results is justified in view of the meager amount of data available.†

2. *Acknowledgments.*—Acknowledgment is made to the ALLIS-CHALMERS MANUFACTURING COMPANY, whose financial support made possible the tests herein reported, and especially to Mr. J. FLETCHER HARPER, Research Engineer, Mr. R. S. MACPHERRAN, Chief Chemist, and Mr. E. H. BROWN, Engineer, Steam Turbine Department, for their helpful suggestions, and for the data they furnished concerning the chemical composition and the foundry history of several of the irons tested.

Acknowledgment is made to Mr. N. J. ALLEMAN, Test Assistant, and to Mr. C. T. HAN, Student Test Assistant, who carried on much of the routine work of actual testing.

These tests have been a part of the work of the Engineering Experiment Station of the University of Illinois, of which DEAN M. S. KETCHUM is the director, and of the Department of Theoretical and Applied Mechanics, of which PROF. M. L. ENGER is the head.

## II. SCOPE OF TESTS, MATERIALS, AND METHODS OF TESTING

3. *Scope of Tests.*—In any investigation of the strength of cast iron, or of any cast metal, two distinct problems are to be recognized: (1)

\*For other reports of the Investigation of the Fatigue of Metals see Bulletins 124, 136, 142, 152, and 156 of the Engineering Experiment Station, University of Illinois.

†For other data on the fatigue strength of cast iron see article by C. H. Bulleid, *Engineering* (London) Oct. 1, 1926.

the study of cast iron as a material, and (2) the study of the effective strength of the material in different parts of a casting. The second problem includes the effect of internal strains, minute cracks, varying rate of cooling of different parts of the casting, inclusions of dirt and slag, and the form assumed by the flakes of graphite in the cast iron. Problem (1), the strength of cast iron as a material, may best be studied by means of tests of specimens cut from castings of simple shape, cast under carefully controlled foundry conditions, since in such parts the cast iron is most nearly uniform in quality and the effects of irregularities are least. It is evident that the study of the effective strength of cast iron in different parts of complicated castings would be a much more difficult matter.

In this bulletin the test results may, in general, be considered as contributions to the study of the strength of cast iron as a material, although one series of tests was made on specimens cut from the inner wall of a large iron cylinder with double walls.

4. *Foundry History of Cast Irons Tested.*—Four different lots of cast iron were tested, and they are hereafter referred to by the laboratory numbers 91, 92, 93, and 94. The specimens of cast iron 91 were cut from a section of a 6-in. cast-iron pipe bought in the open market. This pipe was made by a centrifugal casting process in horizontal sand molds. Figure 1 shows the location of specimens.

Cast irons 92 and 93 were obtained from castings supplied by the Allis-Chalmers Manufacturing Company. The castings were in the form of hollow cylinders with a narrow flange at one end. Cast iron 92 was from a cylinder having a wall approximately 1 in. thick, whose form and size are shown in Fig. 1; and cast iron 93 was from a cylinder having a wall approximately 3 in. thick, whose form and size are also shown in Fig. 1. Both these cylinders were cast in green sand molds having dry sand cores.

Cast iron 94 was from a piece cut from the inner wall of a double-wall cylinder casting. The general location of the slab from which specimens were cut and the location of specimens in the slab are shown in Fig. 2.

5. *Chemical Composition and Metallographic Structure of Cast Irons Tested.*—The chemical composition of cast irons 91, 92, 93, and 94 is given in Table 1. The analyses show no very marked differences and are representative analyses for good gray cast iron.

In Fig. 3 are presented micrographs of unetched samples of the cast irons tested. These show the distribution of the graphite flakes in



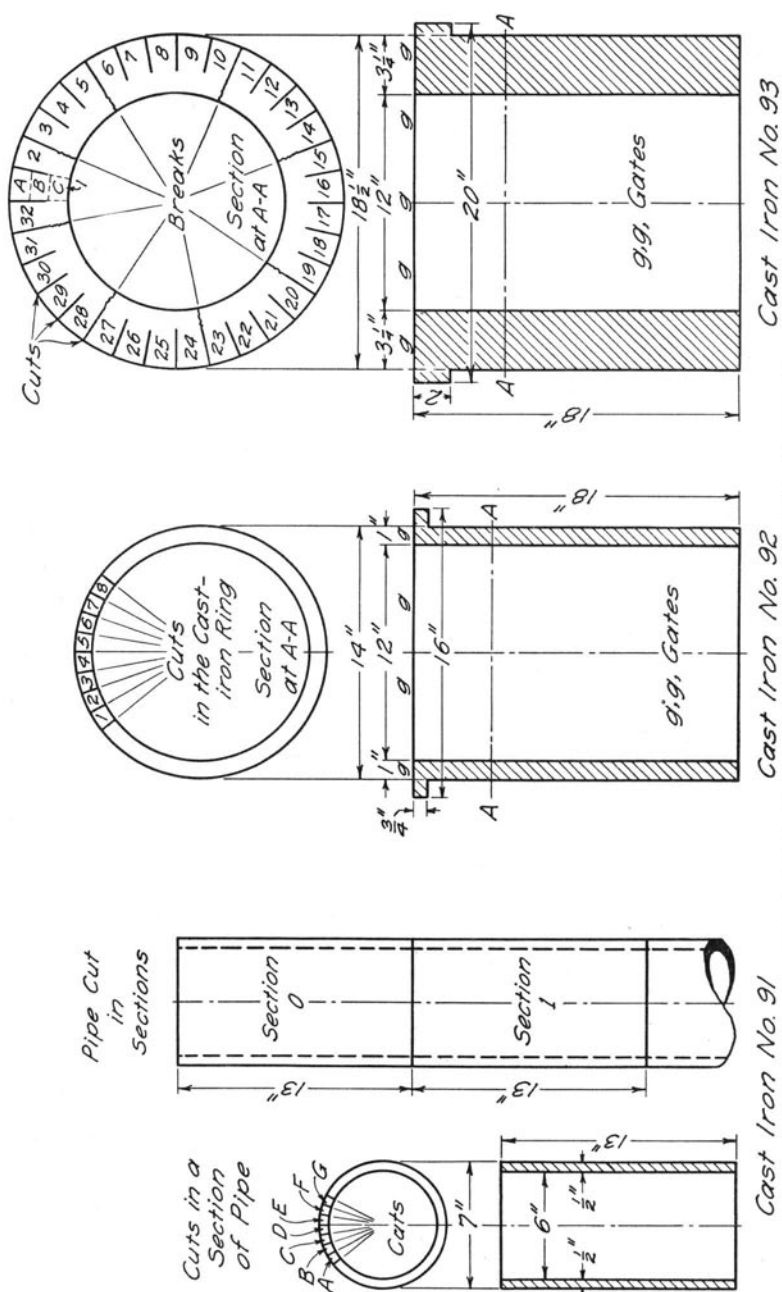


FIG. 1. LOCATION OF SPECIMENS, CAST IRONS 91, 92, AND 93

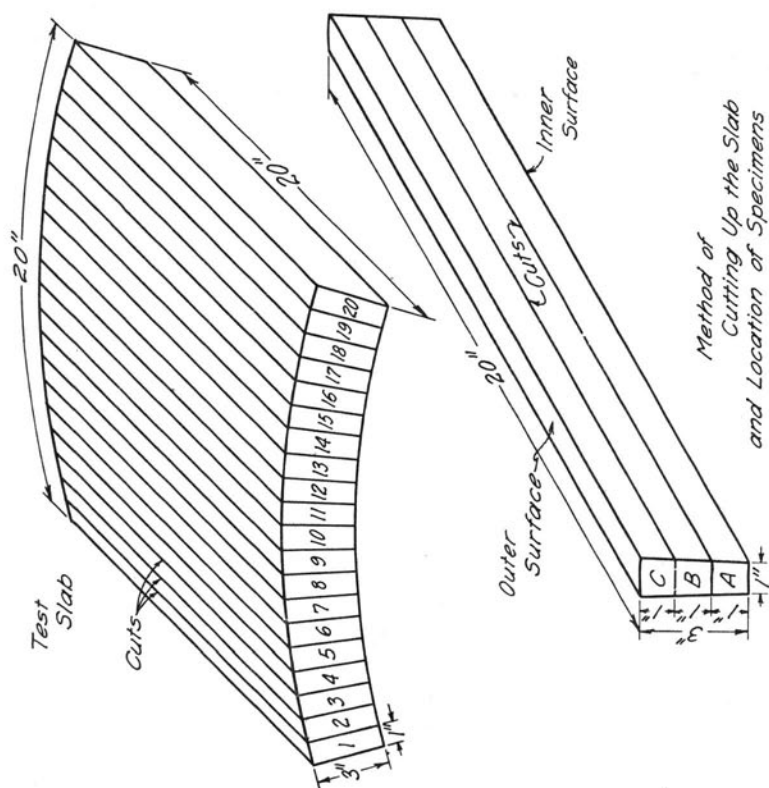
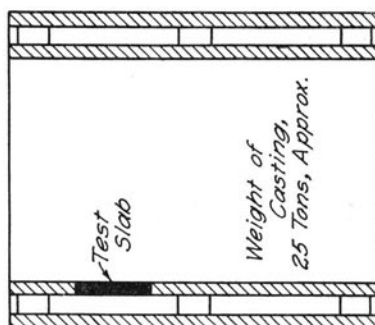
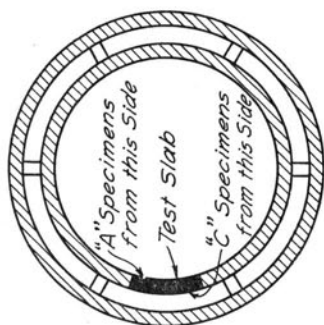


FIG. 2. LOCATION OF SPECIMENS, CAST IRON 94



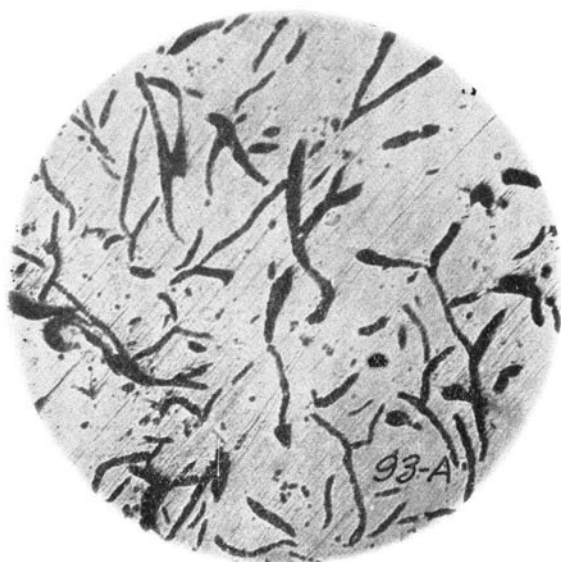


91



92

FIG. 3. MICROGRAPHS OF UNETCHED CAST IRON (x 75)



93-A



93-B

FIG. 3 (CONTINUED). MICROGRAPHS OF UNETCHED CAST IRON (x75)

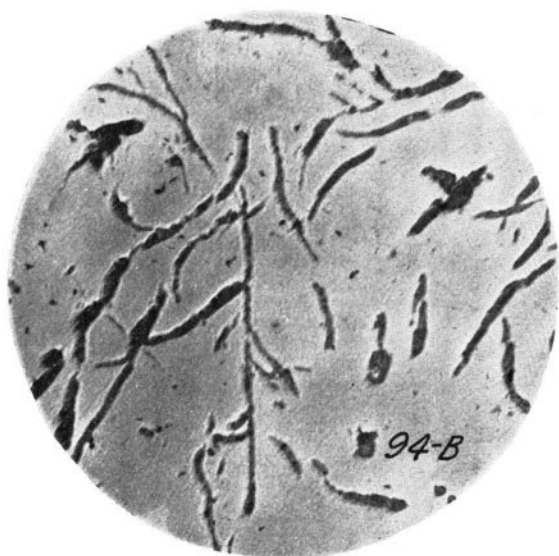


93-C



94-A

FIG. 3 (CONTINUED). MICROGRAPHS OF UNETCHED CAST IRON (x75)



94-B

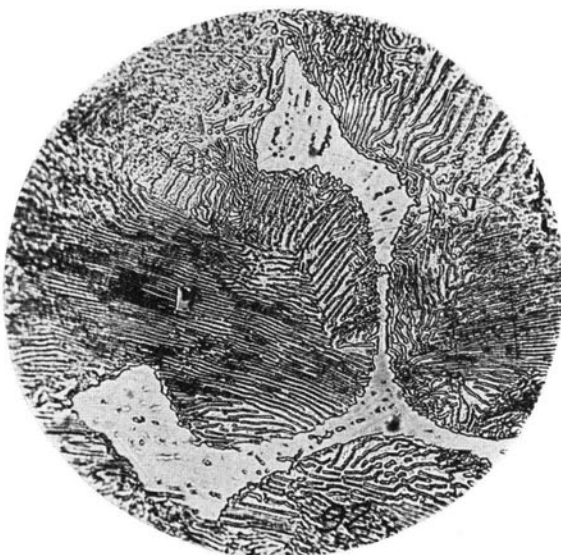


94-C

FIG. 3 (CONCLUDED). MICROGRAPHS OF UNETCHED CAST IRON (x75)



91

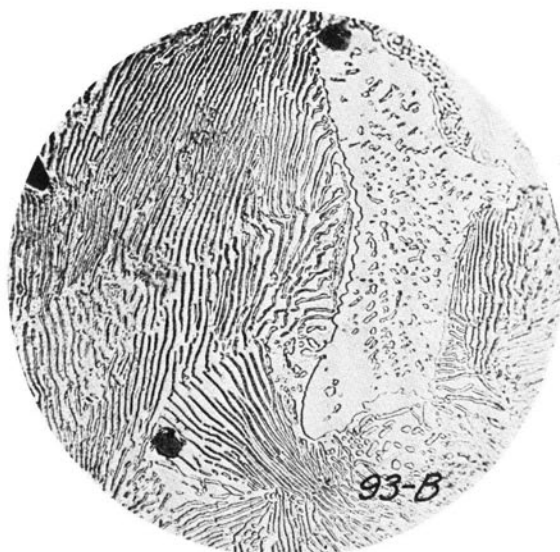


92

FIG. 4. MICROGRAPHS OF ETCHED CAST IRON (x750)  
Etched with 5 per cent picric acid in alcohol.



93-A

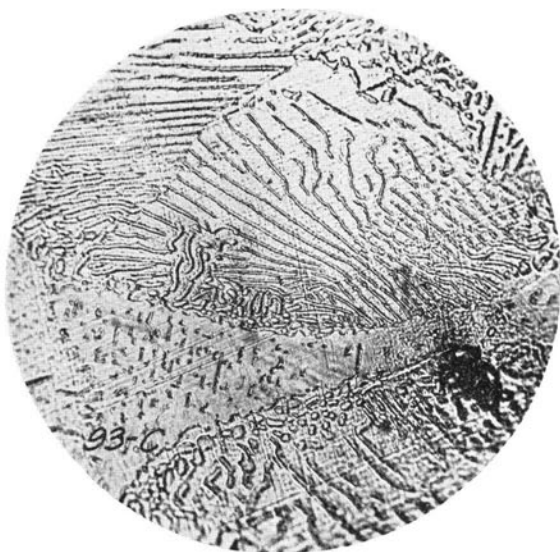


93-B

FIG. 4 (CONTINUED). MICROGRAPHS OF ETCHED CAST IRON (x 750)

Etched with 5 per cent picric acid in alcohol.





93-C. Etched with 5 per cent picric acid in alcohol.

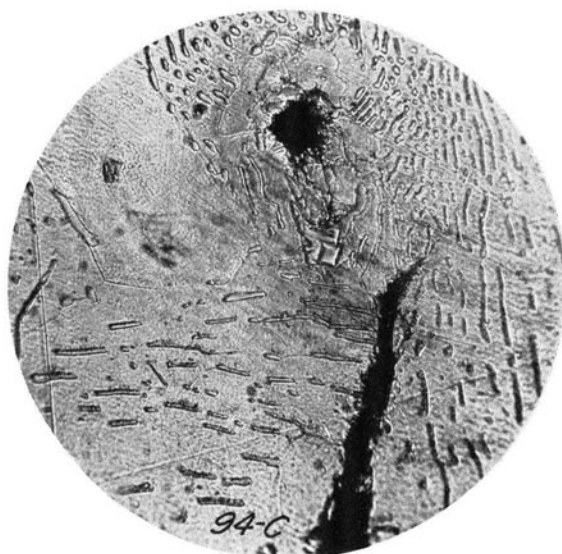


94-A. Etched with 4 per cent nitric acid in alcohol.

FIG. 4 (CONTINUED). MICROGRAPHS OF ETCHED CAST IRON (x 750)



94-B



94-C

FIG. 4 (CONCLUDED). MICROGRAPHS OF ETCHED CAST IRON (x 750)  
Etched with 4 per cent nitric acid in alcohol.

TABLE I  
CHEMICAL COMPOSITION OF CAST IRONS TESTED

Cast Iron	Content, per cent						
	Silicon	Sulphur	Phosphorus	Manganese	Graphitic Carbon	Combined Carbon	Total Carbon
91.....	1.42	0.065	0.75	0.32	2.72	0.84	3.56
92.....	1.10	0.093	0.51	0.62	2.76	0.68	3.44
93A.....	1.10	0.095	0.51	0.63	2.80	0.55	3.35
93B.....	1.10	0.094	0.51	0.59	2.78	0.57	3.35
93C.....	1.10	0.096	0.46	0.60	2.82	0.43	3.25
94A.....	1.16	0.102	0.38	0.58	.....*	.....*	3.32
94B.....	1.14	0.100	0.38	0.61	.....*	.....*	3.30
94C.....	1.13	0.103	0.40	0.57	.....*	.....*	3.30

\*Combined carbon content was less than 0.05 per cent; nearly all the carbon was graphitic.

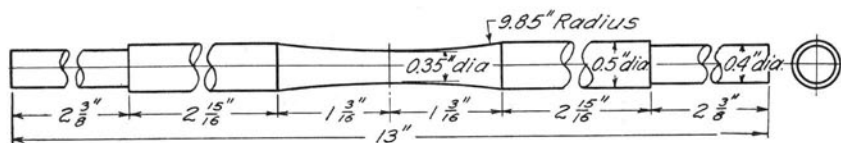
the iron. A fairly extensive microscopic examination of specimens revealed no appreciable segregation of graphite.

In Fig. 4 are presented micrographs of etched specimens taken at higher magnifications than those shown in Fig. 3. The micrographs of Fig. 4 indicate that for cast irons 91, 92, and 93 lamellar pearlite<sup>\*</sup> is the dominant crystalline constituent present. Scattered grains of steadite are discernible in this matrix of lamellar pearlite.

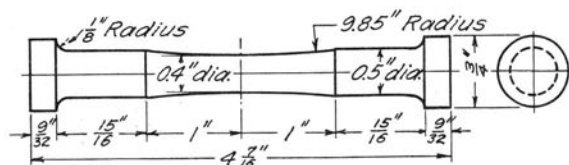
Cast iron 94, which cooled more slowly due to the large mass of the casting, contains its carbon almost entirely in the form of graphite. Ferrite is the dominant crystalline constituent in this case, with scattered areas of pearlite usually grouped around occasional grains of steadite. The pearlite varies from the lamellar form to the globular, with the transition stages in evidence.

All the irons were tested as cast. No special heat treatment was applied either at the foundry or in the laboratory. Cast iron 91 was allowed to cool in the mold instead of being shaken out while still hot, as is quite common practice for centrifugal-cast pipe.

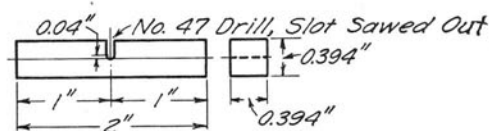
6. *Test Specimens and Methods of Testing.*—Test bars were cut from the pieces of iron furnished as shown in Figs. 1 and 2. These test bars were then cut up into specimens for static tension tests, for Charpy notched-bar tests, for repeated impact tests, and for rotating-beam fatigue tests. The form and size of the specimens used are shown in Fig. 5. It should be noted that since the thickness of the wall of the pipe from which the specimens of cast iron 91 were cut was only  $\frac{1}{2}$  in. it was necessary to make the tension specimen and the rotating-beam specimen for this case slightly smaller than those shown in Fig. 5. The tension specimens of cast iron 91 were made with a minimum diameter



(a)-Rotating-beam Specimen for Fatigue Test



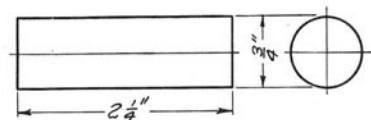
(b)-Specimen for Static Tension Test



(c)-Specimen for Charpy Test



(d)-Specimen for Repeated-impact Test



(e)-Specimen for Static Compression Test

FIG. 5. TEST SPECIMENS

of 0.3 in., and the rotating-beam specimens with a minimum diameter of 0.325 in. and a maximum diameter of 0.400 in.

The tension tests were made on a 100 000-lb. three-screw Olsen testing machine. The tension specimens were specially designed to avoid stress-concentration near the critical section. They were held in Robertson shackles\* shown in Fig. 6, which minimize any flexural action on the

\*See 1921 report of the British Aeronautical Research Committee.

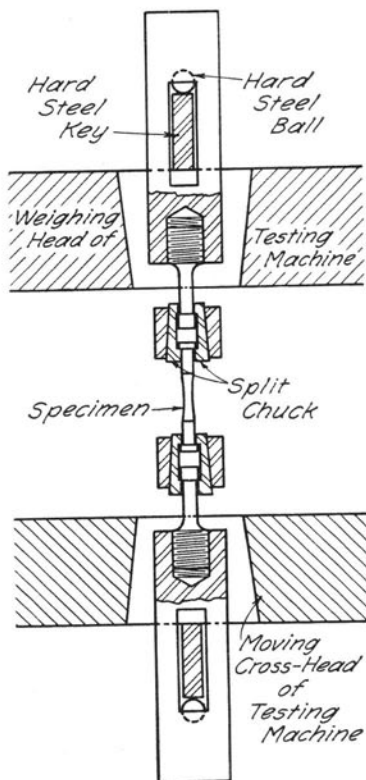


FIG. 6. ROBERTSON SHACKLES FOR TENSION TEST SPECIMENS

specimen. In the case of cast iron 91 tests with specimens of the type shown in Fig. 5b held in Robertson shackles gave a value for ultimate tensile strength about 12 per cent above that obtained for specimens having parallel sides and held in ordinary spherical-seated shackles.

Charpy impact tests were made on a Sauveur and Boylston 30-meter-kilogram testing machine. Repeated impact tests were made on a special double-hammer machine built in the shops of the Department of Theoretical and Applied Mechanics.

Fatigue tests were made on Sondericker (or Farmer) type rotating-beam testing machines. Brinnell tests were made on broken Charpy specimens using an Alpha (Swedish) machine.

The technique of testing, the methods of reducing test data, and a more detailed description of the testing machines used are given in Bulletin 124 of the Engineering Experiment Station of the University of Illinois.

TABLE 2  
TEST DATA OF ROTATING-BEAM FATIGUE TESTS OF CAST IRON  
Speed of Testing Machines, 1500 r.p.m.

Specimen No.	Stress in lb. per sq. in.	Cycles for Rupture	Specimen No.	Stress in lb. per sq. in.	Cycles for Rupture
Cast Iron 91			Cast Iron 93C		
91-M-0.....	18 000	23 500	93-17-C.....	17 000	14 800
91-C-0.....	15 000	97 300	93-27-C.....	14 000	94 100
91-N-0.....	13 000	313 900	93- 4-C.....	12 900	369 100
91-K-0.....	12 500	230 300	93-13-C.....	12 000	141 300
91-I-0.....	12 500	876 200	93- 1-C.....	11 000	431 500
91-E-0.....	12 000	100 799 100*	93- 9-C.....	11 000	203 300
91-G-0.....	11 500	100 026 200*	93-22-C.....	10 380	1 410 700
91-A-0.....	11 000	29 113 800*	93-25-C.....	10 000	214 714 000*
			93-29-C.....	9 500	102 168 800*
Cast Iron 92			Cast Iron 94A		
92-2.....	36 000	900	94-14-A.....	18 000	18 700
92-21.....	23 000	3 900	94-12-A.....	12 000	139 200
92-1.....	17 900	33 900	94- 4-A.....	8 500	967 700
92-24.....	14 000	138 900	94- 6-A.....	7 500	1 705 600
92-22.....	12 000	726 000	94-13-A.....	7 000	55 230 500*
92-3.....	11 500	20 567 700	94-10-A.....	6 550	1 482 400
92-26.....	11 000	4 886 000	94- 8-A.....	6 500	1 033 700
92-20.....	10 750	1 571 800	94- 9-A.....	6 500	49 319 000*
92-60.....	10 500	96 349 900*	94- 5-A.....	6 000	50 116 800*
92-23.....	10 000	15 328 900*			
Cast Iron 93A			Cast Iron 94B		
93-25-A.....	18 000	29 800	94- 6-B.....	15 000	52 800
93-16-A.....	16 000	38 900	94-14-B.....	11 000	182 900
93- 9-A.....	14 800	42 000	94-12-B.....	8 000	1 498 000
93- 5-A.....	13 200	227 800	94-10-B.....	7 500	21 575 600
93-17-A.....	11 000	794 800	94- 4-B.....	7 200	51 440 900*
93-13-A.....	10 000	3 058 900	94- 8-B.....	7 000	37 603 800*
93-21-A.....	10 000	107 971 300*			
93-29-A.....	8 800	113 082 900*			
Cast Iron 93B			Cast Iron 94C		
93-25-B.....	18 000	15 100	94- 6-C.....	15 000	39 900
93- 1-B.....	16 000	19 100	94-14-C.....	11 000	220 500
93-21-B.....	13 000	113 600	94-10-C.....	9 500	381 100
93-29-B.....	12 000	109 500	94- 8-C.....	9 000	35 802 400*
93- 5-B.....	12 000	187 100	94- 4-C.....	8 800	602 200
93- 9-B.....	11 000	451 500	94-12-C.....	8 500	3 700 500
93-13-B.....	10 000	1 868 600	94- 5-C.....	8 000	20 520 200
93-17-B.....	9 500	2 040 300	94- 9-C.....	7 800	50 031 300*
93-27-B.....	9 200	2 832 900			
93-11-B.....	9 000	165 350 300*			
93- 8-B.....	8 800	241 024 500*			

\*Specimen did not fail.

TABLE 3  
RESULTS OF TENSION TESTS, COMPRESSION TESTS, CHARTY TESTS, REPEATED-IMPACT TESTS, BRINELL TESTS, AND FATIGUE TESTS OF CAST IRON

All fatigue tests were made on rotating-beam testing machines

Cast Iron	Static Tension Tests			Ultimate Compressive Strength lb. per sq. in.	Charpy Tests (Notched bar) ft. lb.	Repeated Impact Tests No. of Double Blows	Brinell Number	Fatigue Tests	
	Proportional Elastic Limit	Yield Point	Ultimate Tensile Strength					Endurance Limit lb. per sq. in.	Endurance Ratio*
91.....		.....	26 200	96 000	4.0	1	162	12 000	0.46
92.....		.....	31 600	111 000	11.8	1	148	10 500	0.33
93A.....	Not	.....	28 100	94 000	2.7	1	138	10 000	0.36
93B.....	Clearly	.....	25 300	85 000	2.2	1	132	9 000	0.36
93C.....	Defined	.....	28 000	87 300	2.5	2	139	10 000	0.36
94A.....		.....	21 400	82 500	1.6	3	89	7 000	0.33
94B.....		.....	20 700	83 500	1.6	4	91	7 200	0.35
94C.....		.....	20 500	82 000	1.5	3	88	7 800	0.38

\*The endurance ratio is the ratio of endurance limit to ultimate tensile strength.

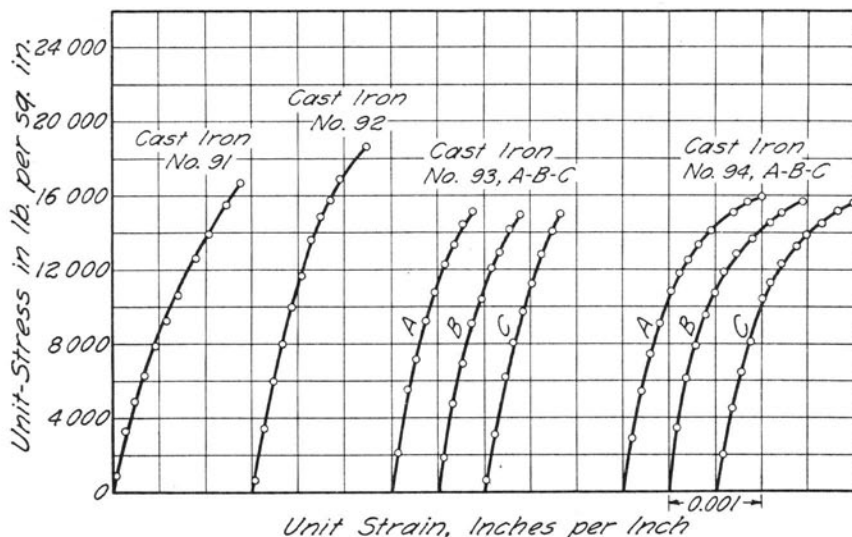


FIG. 7. STRESS-STRAIN DIAGRAMS FOR STATIC TENSION TESTS

See Table 3.

### III. GENERAL TEST DATA AND RESULTS

7. *Static Tension Tests and Brinell Tests.*—The results of the static tension tests are given in Table 3 and typical stress-strain diagrams in Fig. 7. No well-marked proportional elastic limit and no yield point were developed for any tension specimen. The elongation after fracture and the reduction of area for tension test specimens were too small to be measured.

Table 3 also gives the results of the Brinell hardness tests. In the Brinell tests a standard 10 millimeter ball was used, but the load was 1000 kilograms. The Brinell number for a given diameter of impression was taken as one-third that given in the U. S. Bureau of Standards reduction tables for a 3000-kilogram load.

8. *Charpy Notched-bar Tests.*—Table 3 also gives the Charpy notched-bar values obtained. Each value reported is the average of results of tests on from four to six specimens. It will be noted that, as might be expected, the Charpy values, with the exception of those for cast iron 92, are very low compared with those for steel. Charpy values for normalized machine steel of 14 foot-pounds and for heat-treated alloy steel of 45 foot-pounds are not unusual.

9. *Rotating-beam Fatigue Tests.*—Table 2 gives the data of the fatigue tests, and Figs. 8, 9, and 10 the *S-N* diagrams obtained from



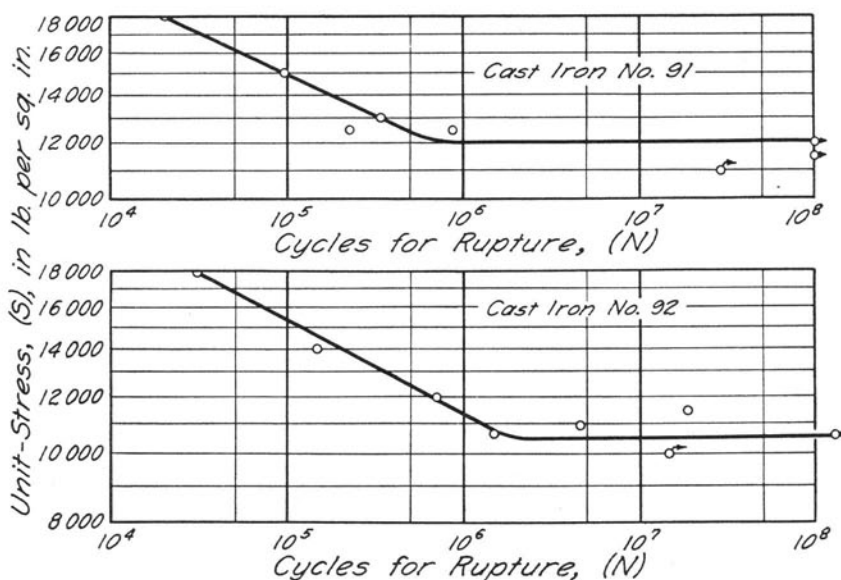


FIG. 8. S-N DIAGRAMS FOR CAST IRONS 91 AND 92

them. Table 3 gives the endurance limits determined from the S-N diagrams, and also the ratio of endurance limit to ultimate tensile strength—the endurance ratio.

For the cast iron tested the endurance ratio averages 0.37, with a high value of 0.46 for cast iron 91. This average value may be compared with an average value of about 0.42 for cast steel\* and an average value of about 0.50 for wrought ferrous metals.†

For cast irons 93 and 94 specimens were cut from the middle of the thickness of the cast piece (B specimens) and also from near the surfaces (A and C specimens, Figs. 1 and 2). For cast iron 93 the specimens from the middle of the thickness showed a slightly lower endurance limit than those from near the surface but the difference was not very marked. For cast iron 94 the metal from the middle of the thickness seemed to be as strong as the average of the specimens from near the two surfaces.

Cast iron 94 is a little lower in total carbon than the other cast irons tested, but has about the same content of graphitic carbon. As suggested on p. 11 it may be regarded as made up of ferrite crystalline grains, a few scattered pearlite grains, and many flakes of graphite. Its static tensile strength, its Brinell hardness and its fatigue strength

\*Univ. of Ill. Eng. Exp. Sta. Bul. 156, p. 16.

†Univ. of Ill. Eng. Exp. Sta. Bul. 136, Fig. 19, p. 53.

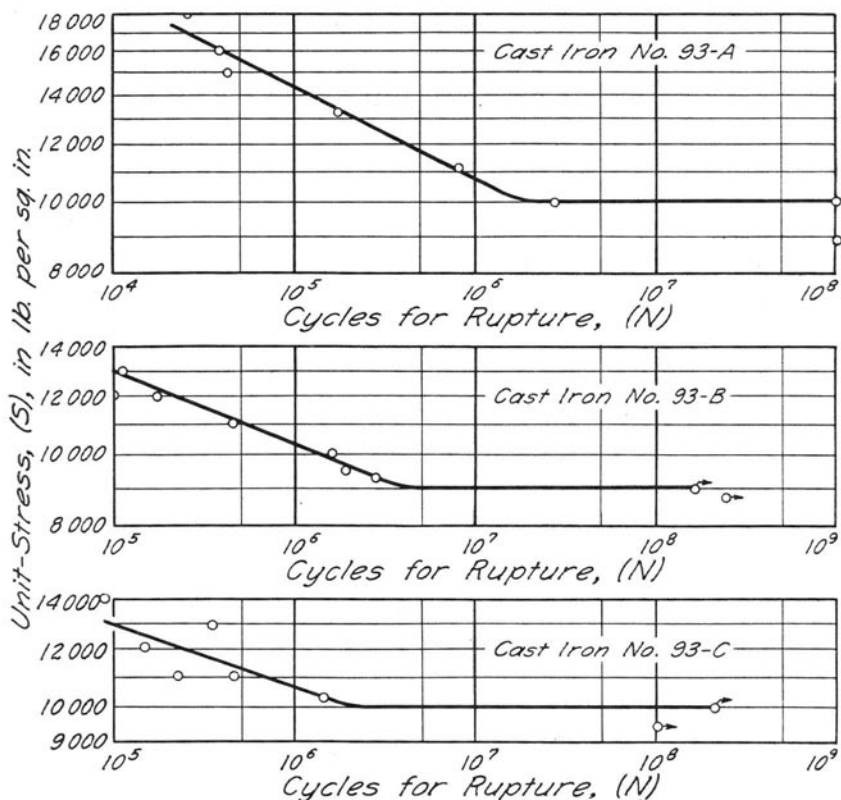


FIG. 9. S-N DIAGRAMS FOR CAST IRON 93

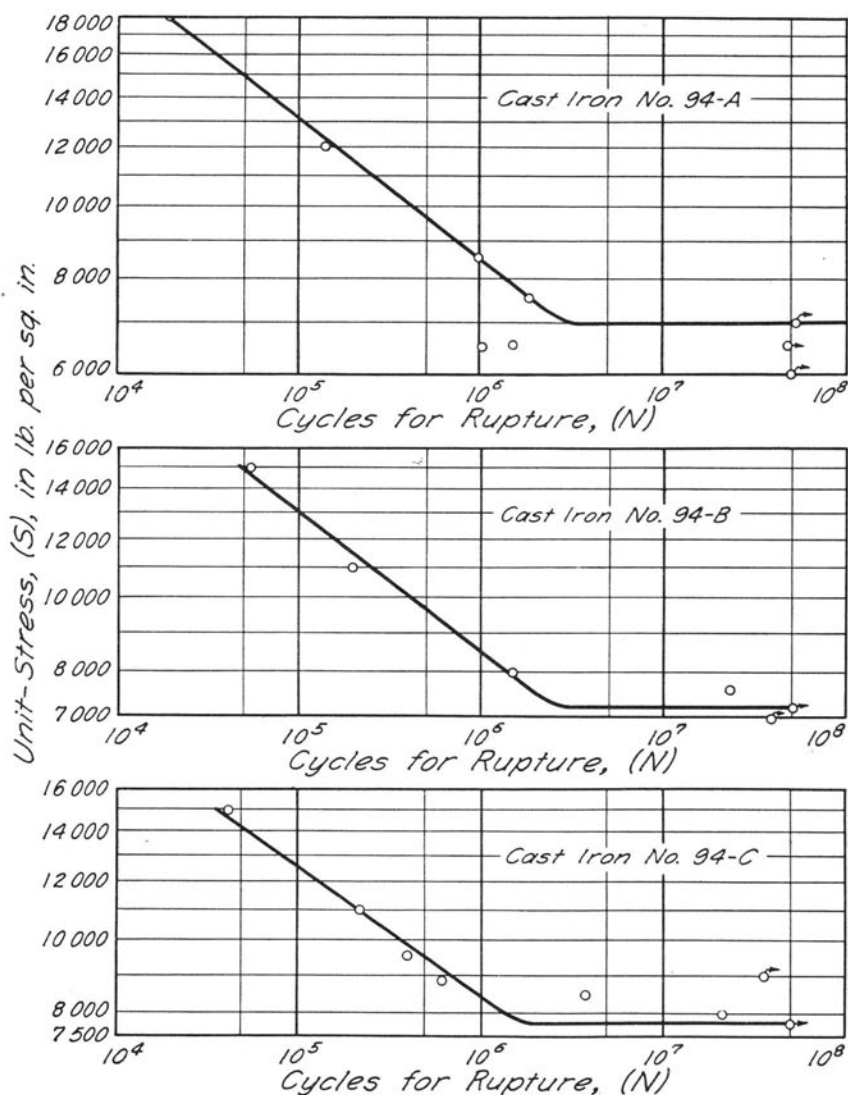
are distinctly lower than those of cast irons 91, 92, and 93. As noted on p. 11 it seems probable that the slow cooling of the large casting, from which the test specimens of cast iron 94 were cut, accounts, in part at least, for the formation of the ferrite grains and the almost complete graphitization of the carbon, with resulting low strength.

#### IV. SPECIAL TESTS

10. *Effect of "Understressing"\* in Raising the Endurance Limit of Cast Iron.*—Several experimenters† have shown that, for certain

\*"Understressing" consists in subjecting a test specimen to a large number of cycles of stress slightly below the endurance limit.

†Moore, R. R., Proc. A.S.T.M., Vol. 24, part II, 1924, p. 565. Univ. of Ill., Eng. Exp. Sta. Bul. 142, p. 27. Gillett and Mack, Proc. A.S.T.M., Vol. 24, part II, 1924, p. 490. Gough, H. J., "The Fatigue of Metals" (Scott, Greenwood & Son), p. 108. Smith, J. H., Jour. (British) Iron and Steel Inst., 1910, part II, p. 280.

FIG. 10.  $S$ - $N$  DIAGRAMS FOR CAST IRON 94

metals, if a fatigue specimen is subjected to a large number of cycles of stress below the endurance limit of the virgin metal, followed by several series of large numbers of cycles with a slightly increased stress for each successive series, the endurance limit may be raised considerably above that of the virgin metal. The largest recorded increase of which

the authors have knowledge is 30 per cent for a 0.37 per cent carbon steel.

It has been commonly thought that this effect of understressing occurred only for metals having a high ductility, as shown by elongation after fracture and reduction of area. As a matter of interest a series of understressing tests were made on specimens of cast irons 93 and 94 and the results of these tests are given in Table 4.

Most of the specimens so tested were first subjected to a run of at least 100 000 000 cycles at a stress equal to or a little less than the endurance limit. After this the stress on the specimen was increased by approximately 500 lb. per sq. in. and a further run of several million cycles given before an addition of stress was made. The entire test was continuous; the testing machine was not stopped until fracture, or the final removal of an unbroken specimen. The increment of stress was the same in all cases but the number of reversals at each stress was smaller in the case of specimen 93-29-C than in the others and the amount by which the endurance limit was raised was found to be less for this specimen. For the tests made, the greater the number of cycles at each stress the greater was the strengthening effect. To see whether the very long initial run of 100 000 000 cycles was a factor of great importance, specimen 93-14-A was given a much shorter initial run, and the result seemed to indicate that a very long initial run was not necessary. The basis on which the percentage increases given in Table 4 have been calculated is as follows: If, under the stress at which the specimen finally fractured, the number of repetitions before fracture exceeded 5 000 000, then the stress at fracture was considered as the new endurance limit; if the number was less than 5 000 000, then the average of the stress at fracture and the preceding stress was considered as the new endurance limit.

It will be seen that in all cases the endurance limit is quite considerably increased, and in the case of specimen 94-5-A the amount of increase (43 per cent) is greater than that usually found with steel.

It seems difficult to reconcile the present results with the theory previously put forward as an explanation of the strengthening effect of reversed stresses. This theory considers understressing as analogous to "cold work." Certain kinds of cold work increase the static and fatigue strength of metals, and the theory regards the action of repeated stresses of an amount insufficient to cause fracture as producing beneficial cold-work conditions, over a small area. The action of reversed stress upon the static properties of a material confirms this view. Experiments\* on steel have shown an increase in static ultimate tensile

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\*Univ. of Ill. Eng. Exp. Sta. Bul. 142, p. 21.

TABLE 4  
TEST DATA OF UNDERSTRESSING\* TESTS ON CAST IRON

Specimen	Original Endurance Limit of Metal lb. per sq. in.	Unit-stress (rotating- beam) lb. per sq. in.	Number of Cycles of Stress	Endurance Limit after Understress- ing lb. per sq. in.	Increase over Original Endurance Limit per cent
93.21 A.....	10 000	10 000 10 400 10 900 11 400 11 900 12 400 12 800 13 300	103 000 000 5 700 000 13 000 000 10 560 000 10 630 000 23 610 000 13 000 000 5 456 000 failed	13 300	33
93.29 A.....	10 000	9 000 9 500 10 000 10 400 10 900 11 400 11 800 12 300	113 000 000 6 078 000 13 080 000 10 800 000 8 800 000 26 061 000 13 250 000 15 400 000 specimen unbroken	not less than 12 300	not less than 23
93 A.....	10 000	9 800 10 300 10 800 11 200 11 700 12 200	14 680 000 10 790 000 12 450 000 15 110 000 14 700 000 7 143 000 failed	12 200	22
93.29 C.....	10 000	9 400 9 900 10 400 10 800 11 300 11 800	102 170 000 6 057 000 4 310 000 4 515 000 4 273 000 4 094 000 failed	11 600	16
93.8 B.....	9 000	8 800 9 300 9 800 10 300 10 800 11 300 11 800	241 025 000 13 900 000 14 310 000 11 205 700 10 163 000 11 183 000 2 096 000 failed	11 600	28
94.5 A.....	7 000	7 500 8 000 8 400 8 900 9 400 9 800 10 300	12 773 000 10 673 000 15 274 000 12 014 000 11 500 000 14 930 000 3 724 000 failed	10 000	43
94.4 B.....	7 200	7 200 7 700 8 100 8 600 9 100	51 441 000 10 956 000 15 584 000 12 887 000 1 103 000 failed	8 800	22

\*"Understressing" consists in subjecting a test specimen to a large number of cycles of stress slightly below the endurance limit.

strength and a decrease in ductility (as measured by percentage reduction of area), after the material has been subjected to many millions of repetitions of a stress almost equal to the endurance limit. This is exactly the effect of static cold work, and the indication is, therefore, that understressing is a form of cold work. However, it should be noted that static cold work may be produced by static *compression* as well as by drawing and rolling. In fact, in commercial cold-rolling and cold-drawing the metal is subjected to heavy compression, which may be the source of the increased strength. The theory mentioned further explains the actual strengthening action of understressing on the grounds that at low stresses slip takes place, and if this slip is not accompanied by the formation of a crack, its effect is to readjust the particles in such a manner that they are better able to resist further slip.\* It would seem, therefore, that the more the material is able to stand permanent deformation without fracture the more the endurance limit may be raised by repeated understressing. If this theory were correct little or no increase in the endurance limit would be expected in the case of cast iron, or any other brittle material, for the absence of ductility (as measured by the usual standards) would lead to the belief that appreciable slip, and consequently any favorable rearrangement of particles, could not take place without failure occurring. The results of the present tests would therefore indicate that either the theory does not offer a complete explanation or else a certain amount of permanent deformation can take place in cast iron subjected to repeated stress.

As previously mentioned, it would appear that the endurance limit of a very ductile material could be raised very considerably by understressing. With the idea of testing the correctness of this point of view and also to obtain some information on the understressing properties of a non-ferrous metal, a series of tests were made on a brass of high ductility (elongation in 2 inches 56 per cent; reduction of area 61 per cent). The results of the understressing tests, given in Table 5, show, however, that comparatively *slight* increases of endurance limit were obtained. Under conditions of loading very similar to those employed with the cast iron the maximum amount by which the endurance limit was raised was 6.1 per cent as against 43 per cent for the cast iron. The experiments on the brass and cast iron seem to show that ductility in tension *as indicated by elongation and reduction of area* is not the factor, at least not the only factor, which determines the ability of the material to have its endurance limit raised by understressing.

Before further discussing the theory of understressing outlined in the preceding pages it would be well to consider if it may be modified

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\*The whole subject of strengthening and strain hardening by cold work has been widely discussed, and several other theories have been presented. For example see Gough and Hansen, Proc. Roy. Soc. A, Vol. 104, 1923.

TABLE 5  
TEST DATA OF UNDERSTRESSING TESTS ON ANNEALED BRASS

Specimen	Original Endurance Limit of Metal lb. per sq. in.	Unit-stress (rotating- beam) lb. per sq. in.	Number of Cycles of Stress	Endurance Limit after Under- stressing lb. per sq. in.	Increase over Original Endurance Limit per cent
105B41A1.....	21 500	20 300 21 100 21 500	10 800 000 10 900 000 4 380 000 failed	21 500	0
105A41A.....	21 500	20 500 21 300 21 700 22 000 22 400 22 800	11 562 000 13 500 000 15 150 000 13 500 000 12 521 000 3 460 000 failed	22 600	5.1
105B29A1.....	21 500	20 100 20 800 21 500 22 200	6 620 000 8 613 000 11 000 000 4 512 000 failed	21 900	2.0
105A29A1.....	21 500	21 100 21 800 22 200 22 600 22 800	12 726 000 15 460 000 23 700 000 20 000 000 13 537 000 failed	22 800	6.1
105A29A2.....	21 500	21 100 22 200	20 000 000 3 406 000 failed	21 600	0.5
105B29A2.....	21 500	20 500 21 700 22 000 22 400 22 800	20 000 000 12 435 000 16 440 000 19 340 000 2 022 000 failed	22 600	5.0

to cover the present experiments on cast iron. If the strengthening effect of reversed stress is due to some rearrangement within crystalline grains by which the weak bonds are strengthened, then, if this rearrangement cannot be made in tension it may be effected during the *compressive* stress period of the cycle. The test results suggest this possibility. To the authors this does not seem difficult to imagine. It appears that compression, in which the particles presumably are brought closer together, is more likely to strengthen a material than tension, in which they are pulled further apart. Again, although cast iron will not withstand appreciable permanent deformation in tension, appreciable permanent deformation in compression may be obtained without fracture.\* Bearing in mind the very large compressive strength of cast iron, it seems probable that for completely reversed stresses fracture occurs due to the failure of the material to withstand the tensile stress of the cycle and that the compressive stress plays little part in the breakdown of the

\*Timoshenko and Lessells, "Applied Elasticity," p. 369.

material. Therefore, if the tensile stress of the cycle is insufficient to start a crack and the cycle is repeated many times, the repetitions of compressive stress may bring the particles of the material into a more favorable position to resist increased tensile stress. With this modification the theory of understressing put forward previous\* to these tests on brittle material seems to offer an explanation consistent with the results of the present tests. If the explanation offered were correct it would then be impossible to raise the endurance limit of cast iron by subjecting it to repetitions of a cycle of stress in which the stress varied from zero to a maximum value in tension. It is hoped that such a series of tests may be made.

Certain static tensile tests were made on cast-iron specimens which had been subjected to many millions of cycles of reversed stress. The results of these tests are shown in Table 6. It will be seen that the static tensile strength shows no signs of increase due to the cycles of understressing. Analogous tests in static *compression* would be of interest.

#### 11. *Effect of Holes and Grooves on the Fatigue Strength of Cast Iron.*—

One very marked limitation of the use of the ordinary formulas of mechanics of materials is that they take no account of localized high stress which is developed at small holes, grooves, and other "stress raisers"† in machine and structural parts.

For some stress raisers the increase above nominal stress can be computed by the more elaborate formulas of the mathematical theory of elasticity, and for others mechanical devices can be used to give a measure of the computed stress. If this localized stress produced its full effect under repetition, it would be expected that the fatigue strength of a specimen in which there was a stress raiser would be reduced from the normal value for the material, and reduced in the same ratio as the stress raiser increased the formula-determined stress.

Fatigue tests on rolled and forged steel have shown that stress raisers do markedly reduce the fatigue strength of a specimen or of a machine part, but that the reduction of fatigue strength is *not so great as is indicated by determinations of theoretical localized stress.*‡ An explanation offered for this discrepancy for steel parts is that the ductility of the metal allows redistribution of stress round a stress raiser before a fatigue crack is formed.

\*Moore, H. F., "The Mechanism of the Fatigue Failure of Metals" Journal of the Franklin Institute, Nov. 1926.

†An apt term coined by Dr. H. W. Gillett of the U. S. Bureau of Standards.

‡Univ. of Ill. Eng. Exp. Sta. Bul. 152, p. 33.

Wilson and Haigh, "The Influence of Rivet Holes on the Strength and Endurance of Steel Structures," Engineering (London), Sept. 8, 1922.

Thomas, W. N., "The Effect of Scratches, etc.," Engineering (London), Oct. 12 and 19, 1923.

Moore, R. R., "Effect of Grooves and Threads, etc.," Proc. A.S.T.M., Vol. 26, part 2, 1926. "Repeated Static and Impact Stresses," Proc. A.S.T.M. Vol. 24, part II, 1924.

Timoshenko and Dietz, Trans. A.S.M.E., 1925, p. 199.



TABLE 6  
TENSILE TEST RESULTS FOR SPECIMENS OF CAST IRON SUBJECTED  
TO UNDERSTRESSING

Specimen	Ultimate Tensile Strength		Remarks
	Virgin Metal	Metal after Understressing	
93.29 A.....	28 000	25 400	Understressed as per Table 4
93.11 B.....	25 300	23 200	Subjected to 100 000 000 cycles of stress just below the endurance limit of the virgin metal.

The ductility of a metal is judged by its elongation after fracture and its reduction of area as given by a tension test. Judged by this standard cast iron is a very brittle material, and might be expected to show a large reduction in fatigue strength due to holes, grooves, or other stress raisers.

Two series of fatigue tests of cast-iron specimens with stress raisers were made. In one series the stress raiser was a groove, and in the other a small radial hole. Cast iron 92 was used for the grooved specimens shown in form and size in Fig. 11. These specimens were held in chucks and run in a rotating-beam testing machine.\* The same tool was employed in cutting all the grooves of each type, and this tool was sharpened, when necessary, a Starrett radius gage being used. The diameter at the bottom of the groove was measured with a pair of thread calipers and a set of Johansson gage blocks, varying by 0.0001 in. in thickness.

The specimens with holes were made of cast iron 93 A, and were of the form and size shown in Fig. 5a with a radial hole 0.055 in. in diameter (No. 54 drill) at the middle of the length.

The test data for the fatigue tests of the cast-iron specimens with holes and with grooves are given in Table 7, and the *S-N* diagrams in Fig. 12. A summary of the test results is given in Table 8. It will be noted in Table 8 that two values of endurance limit are given for specimens with holes—one a value computed by the ordinary flexure formula, taking no account of the hole, and the other a value computed by the ordinary flexure formula taking account of the void in the section when the hole is in a vertical position, but no account of the stress-raising effect of the hole. Since the theoretical stress-concentration factor† is determined on the basis of neglecting the removal of metal by the hole, the “effective” stress-concentration factor is computed on the ratio of the value in column (1) of Table 8 to the value in column (2). However the

\*Univ. of Ill. Eng. Exp. Sta. Bul. 152, Fig. 17, p. 48.

†See footnote to Table 8.

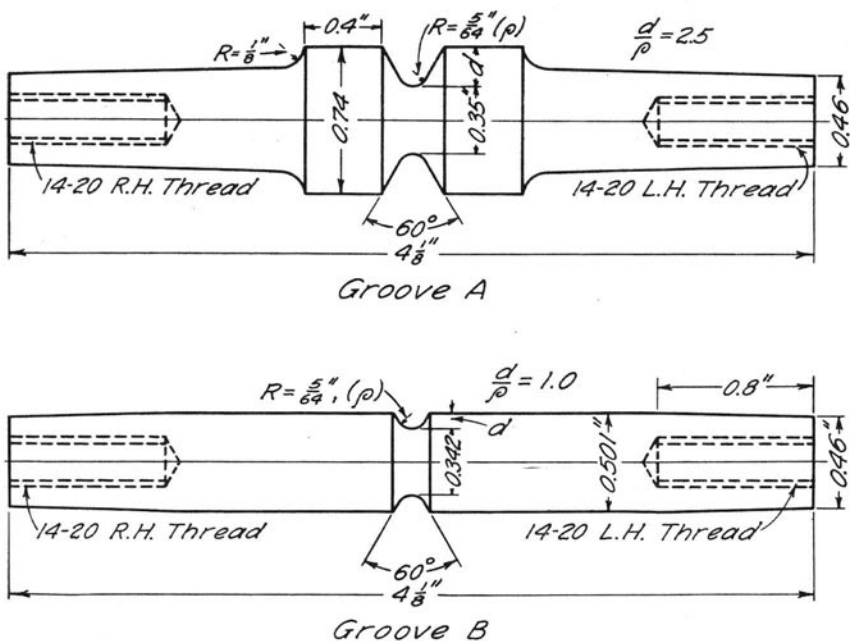


FIG. 11. GROOVED SPECIMENS FOR STRESS-CONCENTRATION TESTS

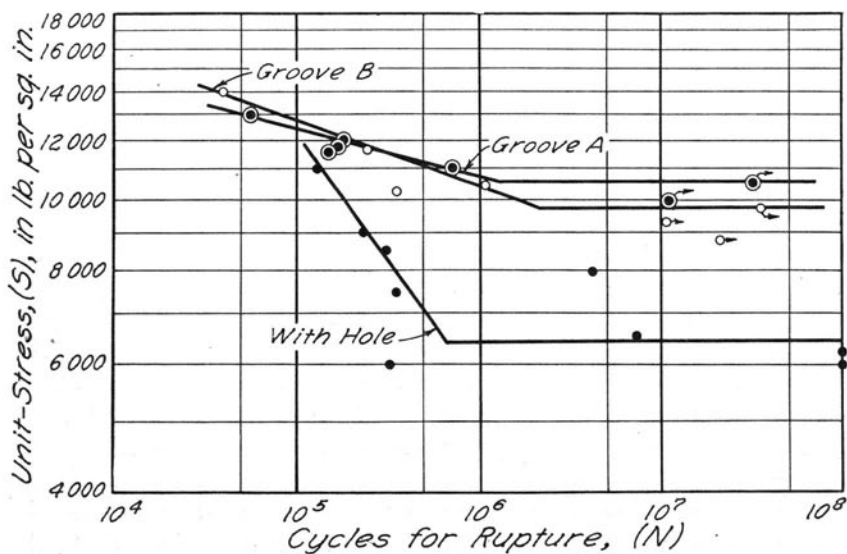


FIG. 12. S-N DIAGRAMS FOR SPECIMENS WITH HOLES AND WITH GROOVES

TABLE 7  
TEST DATA OF FATIGUE TESTS (ROTATING-BEAM) OF CAST-IRON SPECIMENS WITH HOLES AND WITH GROOVES

Specimen	Specimens with radial hole 0.055 in. diameter		Specimens with Groove A (See Fig. 11)				Specimens with Groove B (See Fig. 11)		
	Unit-stress lb. per sq. in.		Specimen	Unit-stress lb. per sq. in.	Number of Cycles of Stress for Fracture	Number of Cycles of Stress for Fracture	Specimen	Unit-stress lb. per sq. in.	Number of Cycles of Stress for Fracture
	Neglecting Removal of Metal by Hole*	Considering Removal of Metal by Hole*							
93.18A.....	11 000	14 800	92.3	13 000	130 400	61 500	92.8†	14 000	38 900
93.2A.....	9 000	12 100	92.2	12 000	229 900	175 000	92.5†	11 800	239 000
93.6A.....	8 600	11 400	92.12†	11 900	311 500	159 000	92.10	10 500	1 094 700
93.22A.....	8 000	10 700	92.1†	11 500	4 261 900	145 000	92.9	10 300	339 000
93.10A.....	7 500	10 200	92.4†	11 000	379 000	704 000	92.11	9 700	34 105 000†
93.7A.....	6 500	8 800	92.12	10 500	7 291 300	39 184 000†	92.5	9 300	10 342 000†
93.20A.....	6 200	8 400	92.1	10 000	193 742 600†	12 375 000†	92.8	8 800	19 700 000†
93.24A.....	6 000	8 200			302 700				
93.27A.....	6 000	8 100			222 000 000†				

\*For detailed explanation of stress values see p. 25.

†Retest.

‡Specimen unbroken.

TABLE 8  
RESULTS OF FATIGUE TESTS OF CAST-IRON SPECIMENS WITH HOLES  
AND WITH GROOVES

Specimens with Radial Holes, Cast Iron 93 A					
Endurance Limits lb. per sq. in.			Stress—intensification Factors*		
Specimens without Hole (1)	Specimens with Hole		Theoretical†	Effective	Ratio
	Neglecting Removal of Metal by Hole (2)	Considering Removal of Metal by Hole (3)	(4)	(1) : (2) (5)	(1) : (3) (6)
10 000	6 400	8 700	3.00	1.56	1.15

Specimens with Grooves, Cast Iron 92						
Endurance Limits lb. per sq. in.			Stress-intensification Factors*			
Specimens without Groove (1)	Specimens with Groove A (2)	Specimens with Groove B (3)	Specimens with Groove A		Specimens with Groove B	
			Theoretical‡ (4)	Effective (1) : (2) (5)	Theoretical‡ (6)	Effective (1) : (3) (7)
10 500	10 500	9 700	3.87	1.00	3.00	1.09

\*Stress-intensification factor is the ratio of stress at the hole, groove, or other "stress raiser" to the nominal stress given by the ordinary formulas of mechanics of materials neglecting the effect of the stress raiser.

†Computed by the formulas of the mathematical theory of elasticity.

‡Computed from the values in the table in the footnote below.

ratio of the value in column (1) to the value in column (3) is of interest as indicating the stress-intensifying effect of the hole over and above the effect of the removal of metal from the cross-section.

With reference to the results for specimens with grooves it may be noted that the theoretical values of the stress-intensification factor were derived from the work of A. A. Griffith.\*

\*"Effect of Surface Scratches on The Strength of Shafts," Adv. Comm. for Aeronautics (British), Dec. 1918.

The theoretical stress-intensification factor for transverse grooves and notches in members under tension, compression, or flexure may be estimated by interpolation in the following table.

Angle between sides of groove, degrees	$d/r$				
	0.5	1	3	5	9
0 (sides parallel).....	2.61	3.02	4.35	5.46	7.94
60.....	2.60	3.00	4.15	5.17	6.98
90.....	2.56	2.92	3.92	4.46	5.46
120.....	2.35	2.62	3.19	3.38	3.73

$d$  = depth of groove.

$r$  = radius of curvature at bottom of groove.

Results not widely different from these may be obtained by using the formula of C. E. Inglis, which is,

$F_t = 1 + 2\sqrt{d/r}$  in which  $F_t$  denotes the stress-concentration factor for an elliptical-bottomed groove in a plate under tension.



FIG. 13. SLIP LINES IN CAST IRON 94-B (x1000)

Etched with 4 per cent nitric acid in alcohol.

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It is seen from Table 8 that the effective stress-concentration is distinctly less than the theoretical. This is especially true for the grooved specimen. The discrepancy between theoretical and effective stress-intensification is greater for cast iron than for the wrought ferrous metals tested.\* Cast iron is emphatically a brittle material and the test results seem, at first glance, to throw doubt upon the explanation which gives stress readjustment by inelastic action as the cause of discrepancy between theoretical and effective stress-intensification.† Cast iron, judged by the usual criteria of elongation and reduction of area, is not at all ductile, yet it can develop without fracture sufficient inelastic strain to permit considerable stress readjustment. Possibly elongation and reduction of area are not reliable indices of the degree (or kind) of ductility necessary for readjustment of stress-distribution in the vicinity of stress raisers.

This suggestion is in line with the fact, discussed in the preceding section, that cast iron shows increase of fatigue strength after many cycles of understressing. It is difficult to conceive how a metal can be so affected unless inelastic slip takes place within the crystals, and some degree of ductility exists.

Now brittleness is regarded as an inherent property of cast iron, since this material ruptures without preliminary visible deformation under steady tensile stress. It is usually felt that such failure must take place without any of the gliding motion which produces slip bands, and which is regarded as evidence of the presence of plastic strain. In the case of cast iron (or any other brittle material) doubt might well be expressed as to the ability of the material to allow internal slip without failure; but in the experiments previously described there were indications that cast iron could suffer some permanent deformation, and consequently experiments were made to detect the effect of stress on the microstructure of this material. A flat specimen of cast iron was made and very carefully polished and then tested in a reversed-flexure testing machine.‡ Figure 13 shows a micrograph at 1000 magnifications taken after a fatigue test at a part of the most highly strained area of a specimen. It seems to the authors that the micrograph shows the presence of slip-bands, and that the area generally shows some distortion due to the straining action. This is additional evidence of permanent deformation of cast iron caused by relative movement of adjacent portions of the same crystal through the action of fatigue.

It may be, however, that the amount of ductility required in order that this gliding action may take place is extremely small—too small to

\*Univ. of Ill. Eng. Exp. Sta. Bul. 152, Table 3, p. 33.

†See in particular Timoshenko and Lessells, "Applied Elasticity," p. 482, and Lessells' letter in *Engineering* (London), Oct. 1, 1926.

‡Univ. of Ill. Eng. Exp. Sta. Bul. 152, p. 73.

be measured in the usual manner in a tensile test. However, on the basis of the present experiments, and assuming the theory of redistribution of stress mentioned previously, the slipping action in cast iron would seem to be greater, or to have a greater effect, than similar action in a material (annealed brass) whose ductility, measured by the usual standards, is very high. There is an indication, therefore, of the presence of a quality in a material similar in action to ductility but not measurable by elongation after fracture or by reduction of area. This quality of the material is the ability of the material to modify, without starting destructive cracks, the conditions of stress and strain caused by the imposition of ranges of stress, more especially when these ranges are within the fatigue range. The extent to which the fatigue range may be increased by repeated understressing, and the weakening effect of imposed stress raisers, are measures of this quality. The test specimens of cast iron, brittle as they were, seemed to possess this "secondary ductility" or "strain adjustability" to a marked degree.

A somewhat different explanation may be put forward to account for the difference between the theoretical and the actual weakening effects of grooves and holes. It seems clear that the reasons for this discrepancy must lie in the *assumptions* made in computing the theoretical stress-intensification, i.e., in the assumptions of the theory of elasticity. The appreciable departure from one such assumption (the linear stress-strain relationship—Hooke's law) has been discussed already and it may be of interest to interpret the present results in the light of a theory which assumes conditions diverging from another assumption. The theory of A. A. Griffith\* explains the discrepancy on the grounds that materials are not homogeneous but are full of extremely minute flaws and other inherent defects; and hence that the introduction of a groove or other form of stress raiser will have a serious effect on the strength only if the dimensions of such a groove are considerably greater than those of the inherent defects in the metal—flaws, inclusions, minute holes, or cracks. In the present experiments, however, the dimensions of the groove and hole are such as to produce very severe theoretical stress-concentration, but the actual weakening effect is shown to be very small.

The Griffith theory may be extended in the following manner to consider the weakening effect of large imposed stress raisers: If the imposed defect (groove, scratch, hole, etc.) is large in comparison with the inherent defects, it seems probable that the stress-concentration at the imposed defect (the base of the groove, the edge of the hole, the

\*"The Phenomena of Rupture and Flow in Solids," Phil. Trans. Roy. Soc. A, Vol. 221, 1921; also "Stress-Concentration in Theory and Practice," Report of Complex Stress Committee, British Assn. Adv. Science, 1921, p. 316.



root of the scratch) is very large, since it may be regarded as the sum of the effect of the imposed defect and the effect of the inherent defects around the imposed defect. In consequence of this very high stress a crack will *start*, and as it spreads away from the region of the imposed defect the stress-concentration due to the latter will decrease, and the stress at the end of the crack may be much less than when it started. The effect of the imposed defect on regions removed from its sphere of influence is, therefore, to produce an imposed defect—the crack—comparable in dimensions with the inherent defects, especially if these are large. According to the extended Griffith theory such an imposed defect is not so weakening as theory would indicate; thus the crack may *start* as theoretical considerations would apparently indicate but the rate of the spread of the crack may be slowed down considerably, and it may *stop* before it spreads to failure.\*

If the inherent defects are large, then the stress raiser acts merely as one more defect and weakens the metal but little in addition. If a piece of metal has a hundred small holes drilled in it at random, it will not be greatly weakened by another small hole, but will be appreciably weakened by a hole ten times the diameter of the small holes, even though the larger hole makes a negligible reduction in the area of the cross-section of the piece.

The inherent defects in cast iron are large flakes of graphite, as shown in Fig. 3. According to the hypothesis just stated stress raisers might be expected to produce less weakening effect in cast iron than in steel in which the inherent defects are probably much smaller. The tests showed this to be the case. With regard to the actual weakening effects produced by the individual stress raisers it will be seen that the most severe stress-concentration in the present tests was caused by the hole. Whereas, according to theory the groove A should have produced the largest effect, actually it produced the least. This difference between the relative effects of groove and hole is not contrary to the theory under discussion. One of the most interesting features of this theory lies in its consideration of the effect of the stress raiser upon material not in the immediate vicinity of the imposed defect. It can be shown that the rate of decrease of the stress with increasing distance from the hole is less rapid than is the rate of decrease of stress from the root of the groove to the center of the specimen. Consequently, the region of influence of a hole is probably greater than that of a small groove. Again, in a rotating-beam test in the ordinary specimen without a hole the extreme outside fibers are subjected to a greater stress than the

\*There is evidence on record of specimens in which final fracture did not occur until several millions of repetitions of stress *after* a crack had been detected, and one or two instances in which a detected crack did not spread to fracture. See Gough, "Fatigue of Metals," p. 165.

inner fibers and consequently the understressing effect of the inner fibers will tend to strengthen the material and increase its resistance to reversals of stress. A radial hole in a specimen increases the stress on the inner fibers and there is less reinforcing action of the outer by the inner fibers than in the specimen without a radial hole. Therefore, the rate of increase of cycles to fracture with decrease of stress should be much less for the specimen with a hole than for the ordinary specimen. The slope of the  $S-N$  diagram in Fig. 12 confirms this.

12. *Tests of Cast Iron at Elevated Temperatures.*—A series of static tension tests and of fatigue tests at elevated temperatures were made on specimens of cast iron 92. The maximum temperature was 1400 deg. F. The testing machine used for the static tests was a 10 000-lb. four-screw Olsen machine. The testing machine used for the fatigue tests was a rotating-spring type testing machine fitted with an electric furnace, shown in diagram in Fig. 14. A thermocouple was held against the specimen at its critical section, and was connected to and controlled the operation of a Leeds and Northrup recorder-controller. The testing machine and the temperature control are described in detail in previous bulletins on the fatigue of metals.\*

Brinell tests at elevated temperatures were made with the 10 000-pound Olsen machine. The Brinell specimen,  $\frac{3}{4}$  in. square by  $\frac{3}{8}$  in. thick, was placed on a block on the weighing table of the testing machine, inside an electrical resistance furnace. The Brinell 10-millimeter ball was mounted on the end of a long bar attached to the moving cross-head of the testing machine. Before the test the moving head was raised well above the furnace so that the ball entered the furnace at room temperature. The temperature of the Brinell specimen was raised to the desired value and maintained constant for at least 15 minutes. The cross-head was then run downwards bringing the ball against the specimen. The pressure employed was 1500 kilograms, except for the tests at 1200 deg. and 1400 deg. F., for which a pressure of 500 kilograms was used. In this way the diameter of impression was kept within a range of between 3.1 and 4.1 mm. In all tests the pressure was maintained for approximately 30 seconds.

The specimen used for static tension tests is shown in Fig. 15 and the arrangement of furnace and specimen in Fig. 16. The specimen used for the fatigue tests is shown in Fig. 17. It was subjected to cycles of reversed flexure at a rate of 1500 cycles per minute.

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\*Univ. of Ill. Eng. Exp. Sta. Bul. 136, p. 97, and Bul. 152, p. 10.

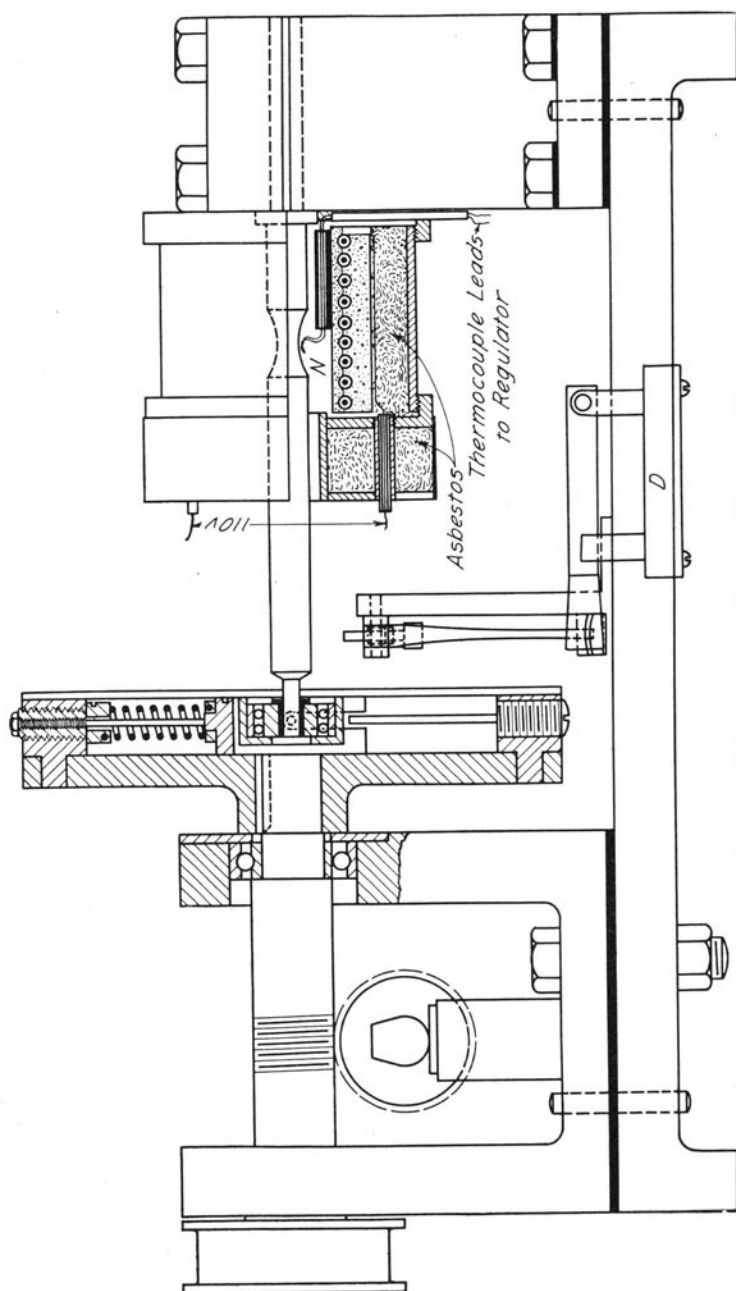


FIG. 14. FATIGUE TESTING MACHINE FOR TESTS AT ELEVATED TEMPERATURES



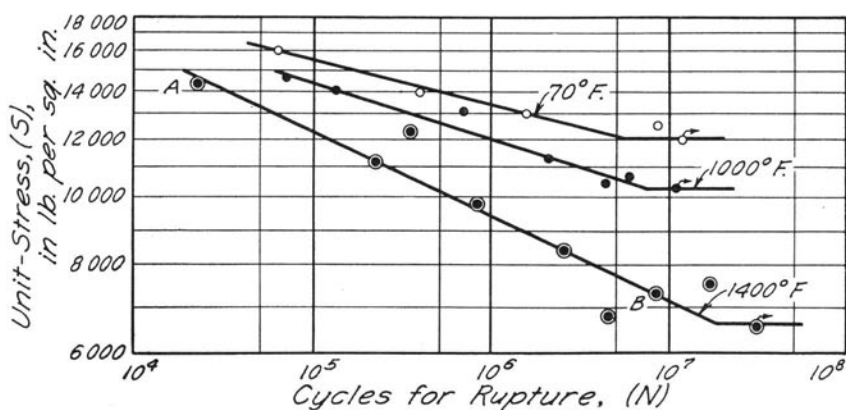


FIG. 18. S-N DIAGRAMS FOR FATIGUE TESTS OF CAST IRON AT ELEVATED TEMPERATURES

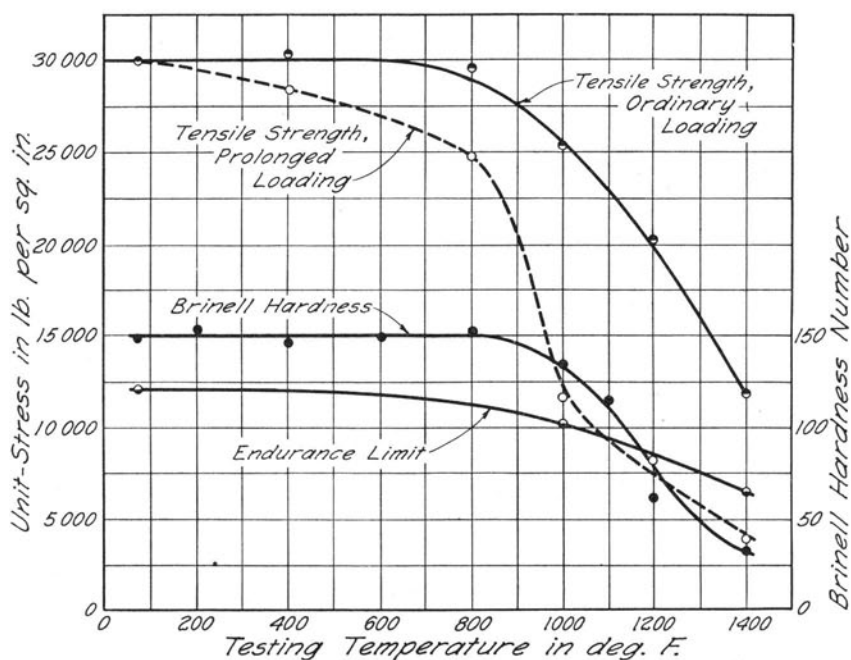


FIG. 19. RESULTS OF TESTS OF CAST IRON AT ELEVATED TEMPERATURES

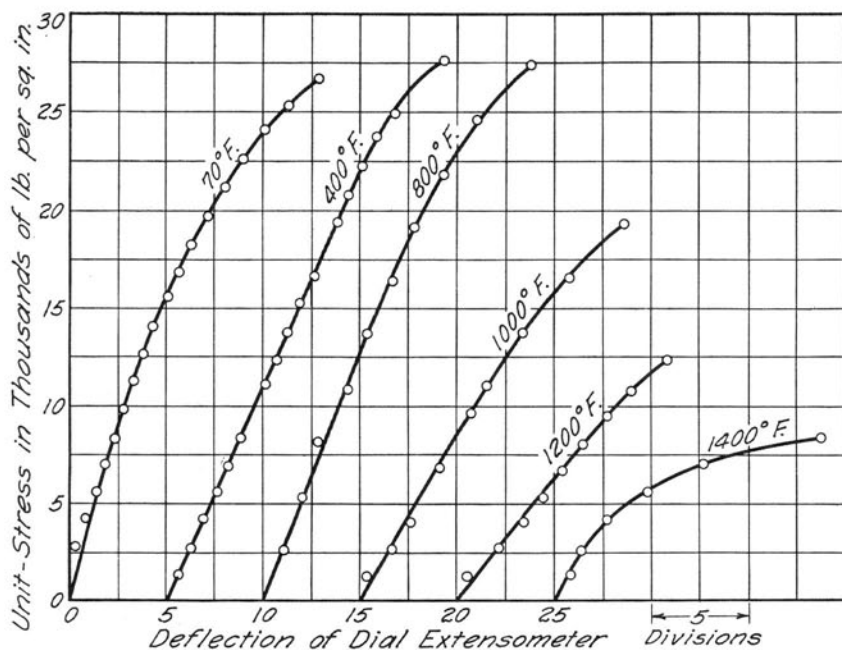


FIG. 20. STRESS-STRAIN DIAGRAMS FOR STATIC TENSION TESTS OF CAST IRON AT ELEVATED TEMPERATURES

TABLE 9  
TEST DATA OF FATIGUE TESTS OF CAST-IRON SPECIMENS AT  
ELEVATED TEMPERATURES

Fatigue tests at elevated temperatures made on a rotating-spring testing machine.

Specimen	Temperature deg. F.	Computed Unit- stress lb. per sq. in.	Number of Cycles of Stress for Fracture	Endurance Limit lb. per sq. in.
92.29.....	70	16 000	66 800	12 000
92.36.....		14 000	400 000	
92.8.....		13 000	1 589 000	
92.40.....		12 500	8 075 000	
92.28.....		11 900	11 940 000*	
92.30.....	1000	14 600	73 700	10 200
92.31.....		14 000	130 000	
92.18.....		13 100	704 000	
92.13.....		11 100	1 963 000	
92.14.....		10 600	5 973 000	
92.28.....		10 300	4 419 000	
92.38.....		10 200	10 006 000*	
92.38.....	1400	14 200	23 000	6 500
92.15.....		12 200	348 000	
92.37.....		11 100	223 000	
92.27.....		9 700	850 000	
92.12.....		8 300	2 531 000	
92.35.....		7 600	16 646 000	
92.19.....		7 200	8 445 000	
92.34.....		6 700	4 499 000	
92.16.....		6 500	30 000 000*	

\*Specimen unbroken.

TABLE 10  
RESULTS OF STATIC TESTS AND FATIGUE TESTS OF CAST IRON AT  
ELEVATED TEMPERATURES

Temperature deg. F.	Brinell Number	Ultimate Tensile Strength (ordinary rate of loading) lb. per sq. in.	Ultimate Tensile Strength (prolonged test) lb. per sq. in.	Endurance Limit lb. per sq. in.
70.....	148	30 000	30 500	12 000
200.....	154	.....	.....	.....
400.....	145	30 500	28 400	.....
600.....	149	.....	.....	.....
800.....	154	29 600	24 900	.....
1000.....	135	25 600	11 800	10 200
1100.....	115	.....	.....	.....
1200.....	60	20 300	7 800	.....
1400.....	32	11 300	3 500	6 500

Table 9 gives the data of the fatigue tests and Table 10 the summarized results of all the tests. The  $S-N$  diagrams for the fatigue tests at elevated temperatures are shown in Fig. 18, and Fig. 19 is a graphical summary of the test results. Figure 20 gives typical stress-strain\* diagrams for the tension tests at elevated temperatures.

The results of the static tests at high temperatures show that the cast iron tested maintains its tensile strength practically constant up to a temperature of at least 800 deg. F., but that at higher temperatures the drop in strength is rapid; this is, of course, in agreement with the results of previous work. Harper and MacPherran† showed that cast iron had an almost constant tensile strength up to about 850 deg. F., although they found the falling off in strength at higher temperatures to be a little more rapid than was indicated by the present tests.

Bach‡ found that the strength of cast iron remained constant up to about 600 deg. F., and that then there was a gradual falling off of strength at temperatures above this such that the strength at 1050 deg. F. was a little more than half its value at ordinary temperature. Howard's§ results indicate a constant ultimate strength up to 900 deg. F., and a value at 1400 deg. F. of a little less than half that at 70 deg. F.

The curve of hardness-temperature follows that of tensile-strength-temperature fairly closely, but at temperatures higher than 1000 deg. F. the drop is more marked and more rapid in the latter than in the former.

\*It is to be remembered that since the extensometer was attached to the specimen holders as shown in Fig. 16 the extensometer readings do not measure precise strain in the specimen, although they do furnish data for showing the general shape of the stress-strain diagrams.

†Harper, J. F. and MacPherran, R. S., "Tensile Tests of Cast Iron at Various Temperatures," Iron Age, Vol. 110, p. 793.

‡Bach, "Elastizität und Festigkeit," 1920, p. 180.

§Howard, J. E., "Physical Properties of Iron and Steel at High Temperature," Iron Age, Vol. 45, p. 585.

Regarding the curves showing the stress-strain relationship at various temperatures in Fig. 20, it must be pointed out that the extensometer used was such that the actual elongation of the specimen under test could not be directly measured, and consequently the actual curves are of stress plotted against corresponding extensometer readings. They do indicate, however, the changes in curvature of the stress-strain relationship with increase of temperature. It will be seen that there is little change in the general slope of the curve up to a temperature of 800 deg. F., and it may also be noted that the relationship at 400 deg. F. and at 800 deg. F. approximately conforms to a straight line law—in fact the curve through the points on the 400-degree test has been drawn as a straight line. This condition is comparable in some respects with that found in tests of a 0.37 per cent carbon steel,\* which showed that the proportional elastic limit was considerably higher at medium temperatures than at room temperature.

The  $S$ - $N$  curves of the fatigue tests of cast iron at high temperatures are shown in Fig. 18. It will be noted that the endurance limit at room temperature found by using the rotating-spring machine is somewhat higher than that found by using the Farmer machine. Previous experiments† have shown the reverse of this to occur and no explanation is offered for the results obtained in the present instance. With regard to the shape of the  $S$ - $N$  diagram obtained at the higher temperatures it is of interest to note that as the temperature is increased the “knee” of the diagram occurs at an increased number of cycles. This is particularly apparent in the case of the curve for 1400 deg. F.

In addition to the static tension tests run at ordinary speeds of testing, other static tension tests were performed at a much slower rate, each test lasting several days. These tests are called “prolonged” tests, and while they were not sufficiently prolonged to give the strength of cast iron under indefinite steady loading, they do furnish an interesting comparison with test results for tests made at ordinary speed, as shown in Table 9 and Fig. 19.

These tests were made in the 10 000-pound Olsen testing machine and the manner of making them was as follows: The specimen was loaded in such a manner that an increment of load was not added until the strain under the previous load had ceased to increase. Indication of increase of strain was given by the fall of the beam of the testing machine, and, in some of the tests, by increase of extensometer readings. When the beam of the testing machine fell it was immediately brought up to

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\*French, H. J. and Tucker, W. A., “Available Data on the Properties of Iron and Steel at Various Temperatures,” Proc. A.S.T.M., Vol. 24, part 2, 1924, p. 56.

†Proc. A.S.T.M., 1924, p. 60, Fig. 3; Univ. of Ill. Eng. Exp. Sta. Bul. 136, p. 79.



the horizontal and the load maintained. This was done repeatedly until a time was reached when the beam remained stationary or fell only after an interval of several hours. The chief point of criticism with respect to the method lies in the assumption that fracture will not occur once the strain has held a constant value for a few hours. At a normal temperature it will be seen that the ultimate strength of cast iron is not affected by the rate of loading (between 0 and about 2000 lb. per sq. in. per sec.)—a result similar to that found by Bauschinger in his tests of cast iron.\* At higher temperatures the difference in ultimate strength due to rate of loading is most marked. In the case of cast iron this is particularly interesting in view of the use of this material in valves and fittings for superheated steam. Although the material appears as strong in ordinary tensile tests at 800 deg. F. as at normal temperature, engineering practice has shown that it is unsafe to use it at temperatures over 500 deg. F.† The present tests show that at temperatures over 500 deg. F. the difference between the ultimate strength with rapid loading and that with slower loading is very great.

A most interesting result is the fact that at very high temperatures the fatigue limit may be greater than the ultimate strength under prolonged loading. A previous bulletin of the Investigation of the Fatigue of Metals‡ reported a similar result and a recent research¶ by Messrs. Tapsell and Bradley of the (British) National Physical Laboratory showed that the fatigue limit may be considerably greater than the ultimate strength under very prolonged loading. In the early days of fatigue testing there was considerable controversy as to whether failure by fatigue depended on time or number of repetitions and although the question has been rather definitely answered in favor of number of repetitions, the present result tends to confirm this conclusion. Under ordinary circumstances repetition of stress above the endurance limit is a damaging factor and repetition of stress below the endurance limit is a strengthening factor. Under elevated temperatures repetition of alternating stress below the endurance limit seems to exert an influence in inhibiting, or at least retarding, the tendency to fail by flow or "creep." It should, of course, be further pointed out that there is a greater departure from a stress-strain proportionality law at higher temperatures than at lower temperatures, as shown in Fig. 20, and consequently a greater difference between the actual and the computed stress on the fatigue specimen.

\*Referred to in Timoshenko and Lessells "Applied Elasticity" p. 380.

†The following is a quotation from the specifications of the A.S.M.E. Boiler Code Committee. "Cast iron shall not be used for nozzles or flanges attached directly to the boiler for any pressure or temperature, nor for boiler and superheater mounting such as connective pipes, fittings, valves and their bonnets, for steam temperatures of over 450 degrees F."

‡Univ. of Ill. Eng. Exp. Sta. Bul. 152, p. 24.

¶Jour. (British) Inst. of Metals, Vol. XXXV, No. 1, 1926 p. 75.

The work of Dickenson\* and others has indicated that at high temperatures metals behave as viscous fluids and the cause of failure after a considerable period at an elevated temperature may be in part due to the internal stress accompanying viscous flow. It is clear that a specimen which fractured after being subjected to 1400 deg. F. for about 20 minutes (specimen A, Fig. 18) may be in quite a different condition of internal stress at fracture from one which fractured after being subjected to 1400 deg. F. for a period of 94 hours (specimen B, Fig. 18). An examination of previous  $S-N$  curves of fatigue tests of other materials at high temperatures reveals the same tendency for the "knee" to be located at high values of  $N$  for high temperature tests. Regarding the endurance limits at the various temperatures, it will be seen that, following the tensile strengths, there is little reduction in endurance limit at a temperature of 1000 deg. F. but at 1400 deg. F. the drop in value is most marked although not so marked as for the tensile strengths. This point is best illustrated by a comparison of the endurance ratios (ratio of endurance limit to ultimate tensile strength) at the three temperatures. At 70 deg. F. the value is 0.400, at 1000 deg. F. it is also 0.400, and at 1400 deg. F. it is 0.574.

13. *Fatigue Strength of Cast Iron under Cycles of Stress Varying from Zero to a Maximum.*—A few tests of cast iron 92 were made to determine endurance limits for cycles of stress varying from zero to a maximum. One series of tests was made by superimposing a steady tensile stress on cycles of reversed flexure. The testing machine used was a rotating-spring machine and the steady load was applied by a compressed spiral spring applying axial tension to the specimen through crossed knife edges. Figure 21 shows the machine in diagram, and Fig. 22 the specimen.†

Another series of tests was made on specimens subjected to cycles of stress varying from nearly zero to a maximum in axial compression. The testing machine used was a spring-type axial stress machine shown in diagram in Fig. 23, and the specimen was of the form and size shown in Fig. 24.‡

Table 11 gives the data of the fatigue tests under varying ranges of stress and Fig. 25 the  $S-N$  diagrams.

In discussing the test results it is convenient to use two terms, defined as follows: (1) *Range of Stress* during a cycle which will be denoted by  $R$ , is the algebraic difference between maximum and mini-

\*Dickenson, J. H. S., "The flow of steels at a red heat" Engineering (London), Vol. 114, 1922, p. 326.

†The machine and the specimen are described in further detail on p. 67 of Univ. of Ill. Eng. Exp. Sta. Bul. 142.

‡The testing machine is described in detail on p. 74 of Univ. of Ill. Eng. Exp. Sta. Bul. 152.

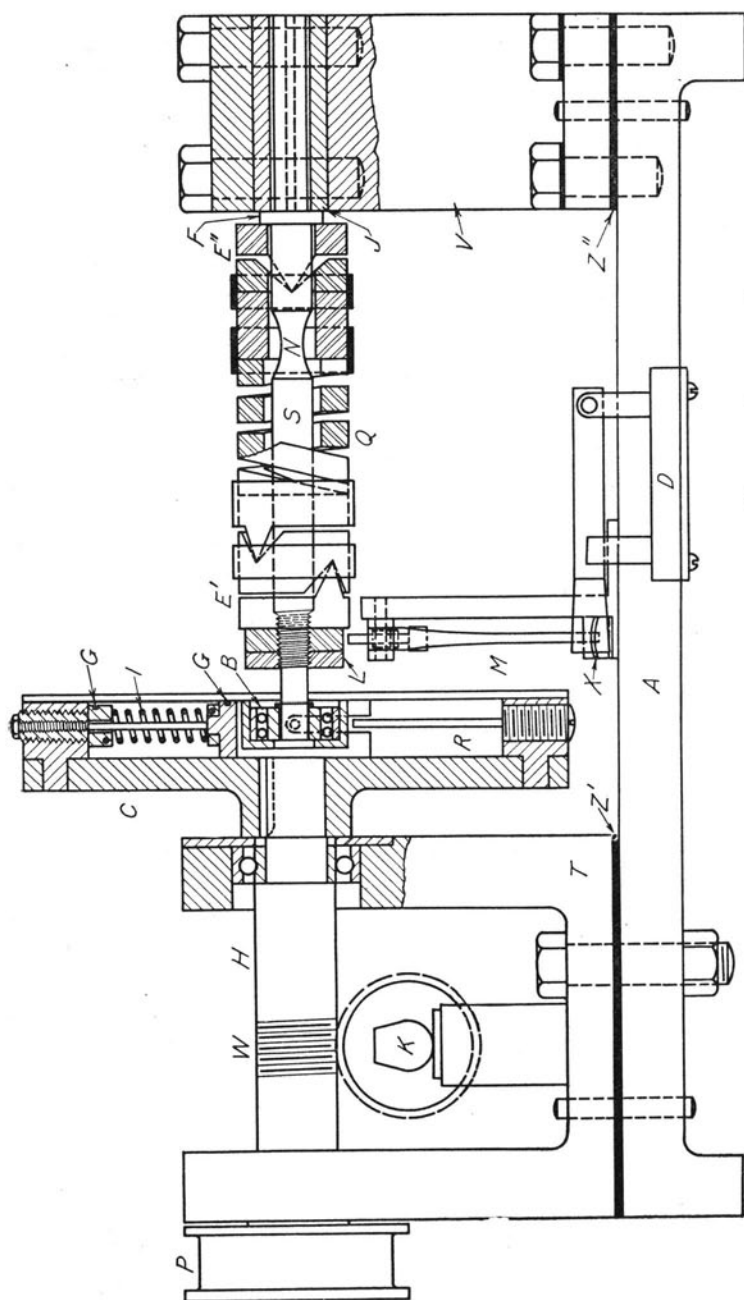


FIG. 21. TESTING MACHINE FOR FATIGUE TESTS WITH VARYING RANGE OF STRESS



TABLE 11

TEST DATA OF FATIGUE TESTS OF SPECIMENS OF CAST IRON UNDER VARIOUS RANGES OF STRESS

Specimen	Ratio of Min. Stress to Max. (range ratio)	Maximum Unit-stress in Cycle	Minimum Unit-stress in Cycle	Range of Stress in Cycle	Number of Cycles of Stress for Fracture	Endurance Limit
		lb. per sq. in.				lb. per sq. in.
92.9.....	0	20 000 t	0	20 000	20 000	15 500
92.17.....		18 300 t	0	18 300	18 300	
92.32.....		15 700 t	0	15 700	951 000	
92.17.....		15 500 t	0	15 500	21 000 000*	
92.34.....		15 000 t	0	15 000	21 000 000*	
92.31.....	-0.2	59 800 c	12 000 t	71 800	600	32 000
92.29.....		45 800 c	9 200 t	55 000	5 300	
92.9.....		38 000 c	7 600 t	45 600	350 400	
92.34.....		34 000 c	6 800 t	40 800	1 635 000	
92.8.....		32 500 c	6 500 t	39 000	2 154 300	
92.17.....		31 800 c	6 400 t	38 200	7 361 000*	
92.17.....	0	82 000 c	0	82 000	4 100	65 000
92.14.....		76 600 c	0	76 600	127 100	
92.28.....		71 800 c	0	71 800	568 100	
92.33.....		68 000 c	0	68 000	1 666 000	
92.32.....		66 800 c	0	66 800	1 890 000	
92.40.....		64 900 c	0	64 900	7 325 700*	
92.17.....		64 600 c	0	64 600	1 190 000*	

\*Specimen unbroken.

t denotes stress in tension; c, stress in compression.

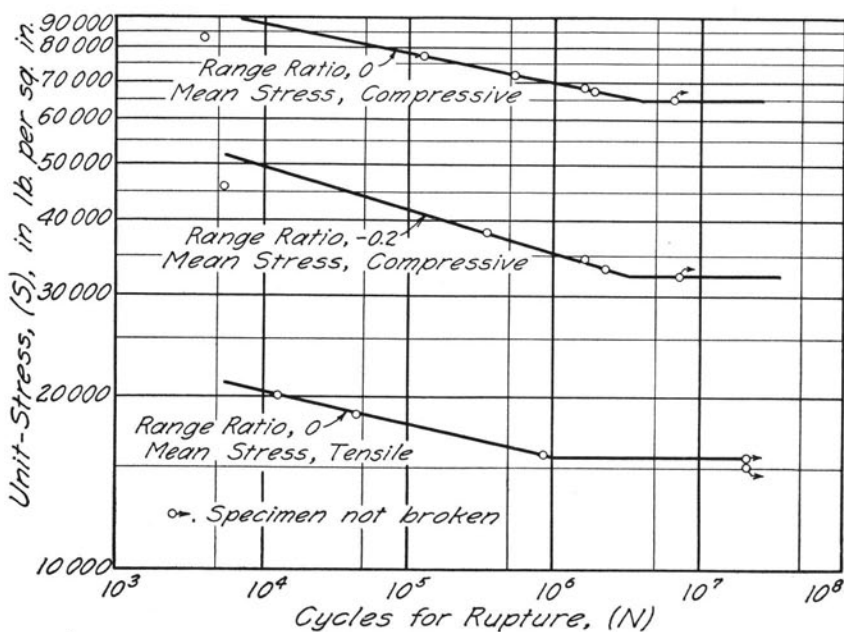


FIG. 25. S-N DIAGRAMS FOR FATIGUE TESTS WITH VARYING RANGE OF STRESS

limit for cycles of stress varying from zero to a maximum ( $r = 0$ ), and  $S_{-1}$  denotes the endurance limit for cycles of completely reversed stress ( $r = -1.0$ ), then for the cast iron tested

$$\frac{S'_0}{S_{-1}} = \frac{15\ 500}{10\ 500} = 1.48$$

For steel specimens under cycles of flexural stress this ratio has been found to range from 1.46 to 1.60,\* so that for cycles in which the stresses are *tensile* this one series of tests indicates that the formulas which have been suggested for steel may be used tentatively for cast iron. If  $S_r$  denotes the endurance limit for cycles of stress whose range ratio is  $r$ , then for *values of  $r$  between  $-1.0$  and  $0$*  any one of the three following formulas seems fairly accurate:

$$\frac{S_r}{S_{-1}} = \sqrt{\frac{2}{1-r^2}}^\dagger$$

$$\frac{S_r}{S_{-1}} = \frac{r+3}{2}^\ddagger$$

$$\frac{S_r}{S_{-1}} = \frac{3}{2-r}$$

For the tests in which cycles of compressive stress were applied to *cast iron* specimens there is introduced a factor which seems to be of no marked influence in tests of *steel* under various ranges of stress.† For steel the compressive strength is about the same as the tensile strength; for cast iron the compressive strength is much greater than the tensile strength. For cast iron 92 the following values were obtained:

Ultimate Tensile Strength,  $S'_U = 31\ 600$  lb. per sq. in.

Ultimate Compressive Strength,  $S''_U = 111\ 000$  lb. per sq. in.

Endurance Limits

Reversed flexure,  $S_{-1} = 10\ 500$  lb. per sq. in.

Zero to max.-tension,  $S'_0 = 15\ 500$  lb. per sq. in.

Zero to max.-compression,  $S''_0 = 65\ 000$  lb. per sq. in.

It will be noted that  $S'_0/S'_U = 0.49$

and that  $S''_0/S''_U = 0.59$

are two values not so very far apart.

The general results of the fatigue tests for varying range of stress are plotted in Fig. 26, following the general plan of the well-known Good-

\*Univ. of Ill. Eng. Exp. Sta. Bul. 142, p. 71.

†Ibid.

‡But see Haigh, "Experiments on the Fatigue of Brasses," Jour. (British) Inst. Metals, Vol. 18, 1918; also see Haigh, "Alternating Stress Tests of Mild Steel," British Ass'n. Complex Stress Committee, Report of 1915.

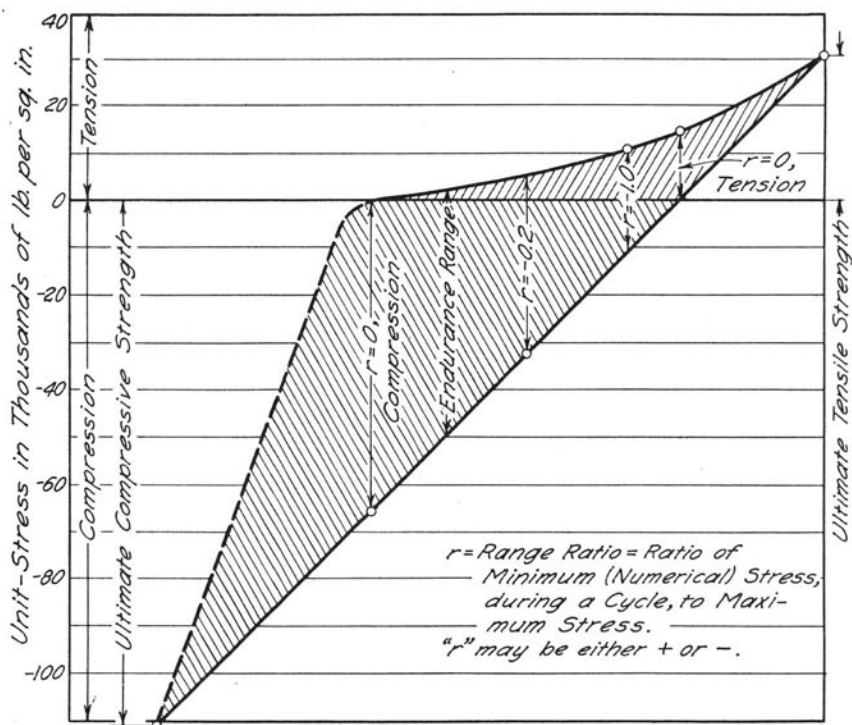


FIG. 26. DIAGRAM FOR VARYING ENDURANCE LIMITS OF CAST IRON WITH VARYING RANGE OF STRESS

man diagram, but extending the diagram into the field of cycles of compressive stress. The part of the diagram shown in broken lines is extrapolated beyond the test data.

Again it is to be noted that these few test data yield results whose publication is justified only by the extreme meagerness of such test data on the fatigue strength of cast iron under varying ranges of stress.

## V. CONCLUSIONS

14. *Summary of Conclusions.*—Static tests, impact tests, and fatigue tests were made on specimens from four different lots of gray cast iron. Cast iron 91 was from a piece of 6-in. pipe with walls  $\frac{1}{2}$  in. thick; this pipe was sand cast by a centrifugal process. Cast iron 92 was from a casting in the form of a 12-in. hollow cylinder with walls 1 in. thick. Cast iron 93 was from a casting in the form of a 12-in. cylinder with walls  $3\frac{1}{4}$  in. thick. Cast iron 94 was from the inner wall of a double walled cylinder casting weighing about 25 tons.

The results of the tests should be regarded as giving some suggestive information concerning the fatigue strength of cast iron rather than as giving comprehensive test data. The results of the tests give information on the properties of gray cast iron as a material rather than on the properties of gray cast iron as found in different parts of castings.

For sketches of castings see Figs. 1 and 2; for microstructures see Figs. 3 and 4.

The following summary of conclusions is given:

(1) The diagrams plotted from the test data of the fatigue tests of cast iron (Figs. 8, 10, and 9) indicate well-defined endurance limits. The regularity of the test data, as shown by the small amount of "scatter" in the plotted points, is surprising in view of the inclusions of slag and the graphite flakes found in cast iron, and the probable internal strains. The regularity of the test data is further emphasized in the stress-strain diagrams, and other graphical test results, reported in this bulletin.

(2) For the cast irons tested the endurance ratios (ratio of endurance limit in reversed flexure to ultimate tensile strength) varied from 0.33 to 0.46, with an average value of 0.35. This average value may be compared with average values of 0.50 for wrought iron and steel and 0.42 for steel castings.

(3) The specimens from the large cylinder casting (cast iron 94) showed lower values both for ultimate tensile strength and for endurance limit than did the specimens from the castings in the shape of pipes (cast irons 91, 92, and 93).

(4) The endurance limit of specimens of cast iron 93 was increased about 30 per cent, and that of specimens of cast iron 94 was increased about 40 per cent by the application of a large number of cycles of stress slightly below the original endurance limit. As an explanation of this result, it is suggested that although cast iron shows very little ductility as measured by elongation and reduction of area in a tension test, it develops some intra-crystalline slip with consequent favorable readjustment of stress-distribution without starting a fatigue crack.

(5) The effect of holes and grooves in reducing the fatigue strength of specimens of cast iron 93 was found to be less than the effect of holes and grooves in steel specimens, and much less than the effect indicated by the theoretical stress-intensification at such irregularities. Two possible explanations are offered: (a) the ductility of cast iron, small as it seems to be, is sufficient to allow considerable slip-adjustment of stress without starting a fatigue



crack (see conclusion 4); and (b) the large graphite flakes in gray iron constitute "stress-raising" defects of a size comparable with the holes and grooves in the specimen, and hence the hole or the groove adds only slightly to the effect of the regions of weakness inherent in the metal.

(6) Tests at elevated temperatures of specimens of cast iron 92 gave little indication of reduction of either ultimate tensile strength (for ordinary speed of testing) or of fatigue strength up to 800 deg. F., and the proportional diminution of fatigue strength under higher temperatures was found to be slightly less than the proportional diminution of ultimate tensile strength and of Brinell hardness.

(7) Tests were made of the fatigue strength of specimens of cast iron 92 under cycles of flexural stress varying from zero to a maximum in tension. The endurance limit was found to be 48 per cent above the endurance limit for cycles of completely reversed stress.

(8) Tests were made of the fatigue strength of specimens of cast iron 92 under cycles of axial stress varying from zero to a maximum in compression. The endurance limit was found to be 59 per cent of the ultimate (static) compressive strength.

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*Bulletin No. 116.* Bituminous Coal Storage Practice, by H. H. Stoek, C. W. Hippard, and W. D. Langtry. 1920. *None available.*

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\**Bulletin No. 121.* The Volute in Architecture and Architectural Decoration, by Rexford Newcomb. 1921. *Forty-five cents.*

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